APPENDIX 2 *Experimental Data*

2A THERMODYNAMIC DATA AT 25°C

Inorganic Substances

Substance	Molar mass, M (g·mol^{-1})	Enthalpy of formation, $\Delta H_f°$ (kJ·mol^{-1})	Free energy of formation, $\Delta G_f°$ (kJ·mol^{-1})	Molar heat capacity, $C_{P,m}$ (J·K^{-1}·mol^{-1})	Molar entropy,* $S_m°$ (J·K^{-1}·mol^{-1})
Aluminum					
Al(s)	26.98	0	0	24.35	28.33
Al^{3+}(aq)	26.98	−524.7	−481.2	—	−321.7
Al_2O_3(s)	101.96	−1675.7	−1582.35	79.04	50.92
$Al(OH)_3$(s)	78.00	−1276	—	—	—
$AlCl_3$(s)	133.33	−704.2	−628.8	91.84	110.67
Antimony					
Sb(s)	121.76	0	0	25.23	45.69
SbH_3(g)	124.78	+145.11	+147.75	41.05	232.78
$SbCl_3$(g)	228.11	−313.8	−301.2	76.69	337.80
$SbCl_5$(g)	299.01	−394.34	−334.29	121.13	401.94
Arsenic					
As(s), gray	74.92	0	0	24.64	35.1
As_2S_3(s)	246.05	−169.0	−168.6	116.3	163.6
AsO_4^{3-}(aq)	138.92	−888.14	−648.41	—	−162.8
Barium					
Ba(s)	137.33	0	0	28.07	62.8
Ba^{2+}(aq)	137.33	−537.64	−560.77	—	+9.6
BaO(s)	153.33	−553.5	−525.1	47.78	70.42
$BaCO_3$(s)	197.34	−1216.3	−1137.6	85.35	112.1
$BaCO_3$(aq)	197.34	−1214.78	−1088.59	—	−47.3
Boron					
B(s)	10.81	0	0	11.09	5.86
B_2O_3(s)	69.62	−1272.8	−1193.7	62.93	53.97
BF_3(g)	67.81	−1137.0	−1120.3	50.46	254.12
Bromine					
Br_2(l)	159.80	0	0	75.69	152.23
Br_2(g)	159.80	+30.91	+3.11	36.02	245.46
Br(g)	79.90	+111.88	+82.40	20.79	175.02
Br^-(aq)	79.90	−121.55	−103.96	—	+82.4
HBr(g)	80.91	−36.40	−53.45	29.14	198.70
Calcium					
Ca(s)	40.08	0	0	25.31	41.42
Ca(g)	40.08	+178.2	+144.3	20.79	154.88
Ca^{2+}(aq)	40.08	−542.83	−553.58	—	−53.1

(continued)

Inorganic Substances *(continued)*

Substance	Molar mass, M (g·mol^{-1})	Enthalpy of formation, $\Delta H_f°$ (kJ·mol^{-1})	Free energy of formation, $\Delta G_f°$ (kJ·mol^{-1})	Molar heat capacity, $C_{P,m}$ (J·K^{-1}·mol^{-1})	Molar entropy,* $S_m°$ (J·K^{-1}·mol^{-1})
$CaO(s)$	56.08	−635.09	−604.03	42.80	39.75
$Ca(OH)_2(s)$	74.10	−986.09	−898.49	87.49	83.39
$Ca(OH)_2(aq)$	74.10	−1002.82	−868.07	—	−74.5
$CaCO_3(s)$, calcite	100.09	−1206.9	−1128.8	81.88	92.9
$CaCO_3(s)$, aragonite	100.09	−1207.1	−1127.8	81.25	88.7
$CaCO_3(aq)$	100.09	−1219.97	−1081.39	—	−110.0
$CaF_2(s)$	78.08	−1219.6	−1167.3	67.03	68.87
$CaF_2(aq)$	78.08	−1208.09	−1111.15	—	−80.8
$CaCl_2(s)$	110.98	−795.8	−748.1	72.59	104.6
$CaCl_2(aq)$	110.98	−877.1	−816.0	—	59.8
$CaBr_2(s)$	199.88	−682.8	−663.6	72.59	130
$CaC_2(s)$	64.10	−59.8	−64.9	62.72	69.96
$CaSO_4(s)$	136.14	−1434.11	−1321.79	99.66	106.7
$CaSO_4(aq)$	136.14	−1452.10	−1298.10	—	−33.1
Carbon (for organic compounds, see the next table)					
C(s), graphite	12.01	0	0	8.53	5.740
C(s), diamond	12.01	+1.895	+2.900	6.11	2.377
C(g)	12.01	+716.68	+671.26	20.84	158.10
$CO(g)$	28.01	−110.53	−137.17	29.14	197.67
$CO_2(g)$	44.01	−393.51	−394.36	37.11	213.74
$CO_3^{2-}(aq)$	60.01	−677.14	−527.81	—	−56.9
$CCl_4(l)$	153.81	−135.44	−65.21	131.75	216.40
$CS_2(l)$	76.15	+89.70	+65.27	75.7	151.34
HCN(g)	27.03	+135.1	+124.7	35.86	201.78
HCN(l)	27.03	+108.87	+124.97	70.63	112.84
HCN(aq)	27.03	+107.1	+119.7	—	124.7
Cerium					
Ce(s)	140.12	0	0	26.94	72.0
$Ce^{3+}(aq)$	140.12	−696.2	−672.0	—	−205
$Ce^{4+}(aq)$	140.12	−537.2	−503.8	—	−301
Chlorine					
$Cl_2(g)$	70.90	0	0	33.91	223.07
Cl(g)	35.45	121.68	105.68	21.84	165.20
$Cl^-(aq)$	35.45	−167.16	−131.23	—	+56.5
HCl(g)	36.46	−92.31	−95.30	29.12	186.91
HCl(aq)	36.46	−167.16	−131.23	—	56.5
Copper					
Cu(s)	63.55	0	0	24.44	33.15
$Cu^+(aq)$	63.55	+71.67	+49.98	—	+40.6
$Cu^{2+}(aq)$	63.55	+64.77	+65.49	—	−99.6
$Cu_2O(s)$	143.10	−168.6	−146.0	63.64	93.14
$CuO(s)$	79.55	−157.3	−129.7	42.30	42.63
$CuSO_4(s)$	159.61	−771.36	−661.8	100.0	109
$CuSO_4·5H_2O(s)$	249.69	−2279.7	−1879.7	280	300.4

Substance	Molar mass, M (g·mol^{-1})	Enthalpy of formation, ΔH_f° (kJ·mol^{-1})	Free energy of formation, ΔG_f° (kJ·mol^{-1})	Molar heat capacity, $C_{P,m}$ (J·K^{-1}·mol^{-1})	Molar entropy,* S_m° (J·K^{-1}·mol^{-1})
Deuterium					
$D_2(g)$	4.028	0	0	29.20	144.96
$D_2O(g)$	20.028	−249.20	−234.54	34.27	198.34
$D_2O(l)$	20.028	−294.60	−243.44	34.27	75.94
Fluorine					
$F_2(g)$	38.00	0	0	31.30	202.78
$F^-(aq)$	19.00	−332.63	−278.79	—	−13.8
HF(g)	20.01	−271.1	−273.2	29.13	173.78
HF(aq)	20.01	−330.08	−296.82	—	88.7
Hydrogen (see also Deuterium)					
$H_2(g)$	2.0158	0	0	28.82	130.68
H(g)	1.0079	+217.97	+203.25	20.78	114.71
$H^+(aq)$	1.0079	0	0	0	0
$H_2O(l)$	18.02	−285.83	−237.13	75.29	69.91
$H_2O(g)$	18.02	−241.82	−228.57	33.58	188.83
$H_2O_2(l)$	34.02	−187.78	−120.35	89.1	109.6
$H_2O_2(aq)$	34.02	−191.17	−134.03	—	143.9
$H_3O^+(aq)$	19.02	−285.83	−237.13	75.29	+69.91
Iodine					
$I_2(s)$	253.80	0	0	54.44	116.14
$I_2(g)$	253.80	+62.44	+19.33	36.90	260.69
$I^-(aq)$	126.90	−55.19	−51.57	—	+111.3
HI(g)	127.91	+26.48	+1.70	29.16	206.59
Iron					
Fe(s)	55.84	0	0	25.10	27.28
$Fe^{2+}(aq)$	55.84	−89.1	−78.90	—	−137.7
$Fe^{3+}(aq)$	55.84	−48.5	−4.7	—	−315.9
$Fe_3O_4(s)$, magnetite	231.52	−1118.4	−1015.4	143.43	146.4
$Fe_2O_3(s)$, hematite	159.68	−824.2	−742.2	103.85	87.40
FeS(s, α)	87.90	−100.0	−100.4	50.54	60.29
FeS(aq)	87.90	—	+6.9	—	—
$FeS_2(s)$	119.96	−178.2	−166.9	62.17	52.93
Lead					
Pb(s)	207.2	0	0	26.44	64.81
$Pb^{2+}(aq)$	207.2	−1.7	−14.43	—	+10.5
$PbO_2(s)$	239.2	−277.4	−217.33	64.64	68.6
$PbSO_4(s)$	303.3	−919.94	−813.14	103.21	148.57
$PbBr_2(s)$	367.0	−278.7	−261.92	80.12	161.5
$PbBr_2(aq)$	367.0	−244.8	−232.34	—	175.3
Magnesium					
Mg(s)	24.31	0	0	24.89	32.68
Mg(g)	24.31	+147.70	+113.10	20.79	148.65

(continued)

Inorganic Substances *(continued)*

Substance	Molar mass, M (g·mol^{-1})	Enthalpy of formation, $\Delta H_f°$ (kJ·mol^{-1})	Free energy of formation, $\Delta G_f°$ (kJ·mol^{-1})	Molar heat capacity, $C_{P,m}$ (J·K^{-1}·mol^{-1})	Molar entropy,* $S_m°$ (J·K^{-1}·mol^{-1})
$Mg^{2+}(aq)$	24.31	−466.85	−454.8	—	−138.1
$MgO(s)$	40.31	−601.70	−569.43	37.15	26.94
$MgCO_3(s)$	84.32	−1095.8	−1012.1	75.52	65.7
$MgBr_2(s)$	184.11	−524.3	−503.8	—	117.2
Mercury					
$Hg(l)$	200.59	0	0	27.98	76.02
$Hg(g)$	200.59	+61.32	+31.82	20.79	174.96
$HgO(s)$	216.59	−90.83	−58.54	44.06	70.29
$Hg_2Cl_2(s)$	472.08	−265.22	−210.75	102	192.5
Nitrogen					
$N_2(g)$	28.02	0	0	29.12	191.61
$NO(g)$	30.01	+90.25	+86.55	29.84	210.76
$N_2O(g)$	44.02	+82.05	+104.20	38.45	219.85
$NO_2(g)$	46.01	+33.18	+51.31	37.20	240.06
$N_2O_4(g)$	92.02	+9.16	+97.89	77.28	304.29
$HNO_3(l)$	63.02	−174.10	−80.71	109.87	155.60
$HNO_3(aq)$	63.02	−207.36	−111.25	—	146.4
$NO_3^-(aq)$	62.02	−205.0	−108.74	—	+146.4
$NH_3(g)$	17.03	−46.11	−16.45	35.06	192.45
$NH_3(aq)$	17.03	−80.29	−26.50	—	111.3
$NH_4^+(aq)$	18.04	−132.51	−79.31	—	+113.4
$NH_2OH(s)$	33.03	−114.2	—	—	—
$HN_3(g)$	43.04	+294.1	+328.1	98.87	238.97
$N_2H_4(l)$	32.05	+50.63	+149.34	139.3	121.21
$NH_4NO_3(s)$	80.05	−365.56	−183.87	84.1	151.08
$NH_4Cl(s)$	53.49	−314.43	−202.87	—	94.6
$NH_4ClO_4(s)$	117.49	−295.31	−88.75	—	186.2
Oxygen					
$O_2(g)$	32.00	0	0	29.36	205.14
$O_3(g)$	48.00	+142.7	+163.2	39.29	238.93
$OH^-(aq)$	17.01	−229.99	−157.24	—	−10.75
Phosphorus					
$P(s)$, white	30.97	0	0	23.84	41.09
$P_4(g)$	123.88	+58.91	+24.44	67.15	279.98
$PH_3(g)$	33.99	+5.4	+13.4	37.11	210.23
$P_4O_{10}(s)$	283.88	−2984.0	−2697.0	—	228.86
$H_3PO_3(aq)$	81.99	−964.8	—	—	—
$H_3PO_4(l)$	97.99	−1266.9	—	—	—
$H_3PO_4(aq)$	97.99	−1288.34	−1142.54	—	158.2
$PCl_3(l)$	137.32	−319.7	−272.3	—	217.18
$PCl_3(g)$	137.32	−287.0	−267.8	71.84	311.78
$PCl_5(g)$	208.22	−374.9	−305.0	112.8	364.6
$PCl_5(s)$	208.22	−443.5	—	—	—

Substance	Molar mass, M (g·mol^{-1})	Enthalpy of formation, ΔH_f° (kJ·mol^{-1})	Free energy of formation, ΔG_f° (kJ·mol^{-1})	Molar heat capacity, $C_{P,m}$ (J·K^{-1}·mol^{-1})	Molar entropy,* S_m° (J·K^{-1}·mol^{-1})
Potassium					
K(s)	39.10	0	0	29.58	64.18
K(g)	39.10	+89.24	+60.59	20.79	160.34
K^+(aq)	39.10	−252.38	−283.27	—	+102.5
KOH(s)	56.11	−424.76	−379.08	64.9	78.9
KOH(aq)	56.11	−482.37	−440.50	—	91.6
KF(s)	58.10	−567.27	−537.75	49.04	66.57
KCl(s)	74.55	−436.75	−409.14	51.30	82.59
KBr(s)	119.00	−393.80	−380.66	52.30	95.90
KI(s)	166.00	−327.90	−324.89	52.93	106.32
$KClO_3$(s)	122.55	−397.73	−296.25	100.25	143.1
$KClO_4$(s)	138.55	−432.75	−303.09	112.38	151.0
K_2S(s)	110.26	−380.7	−364.0	—	105
K_2S(aq)	110.26	−471.5	−480.7	—	190.4
Silicon					
Si(s)	28.09	0	0	20.00	18.83
SiO_2(s, α)	60.09	−910.94	−856.64	44.43	41.84
Silver					
Ag(s)	107.87	0	0	25.35	42.55
Ag^+(aq)	107.87	+105.58	+77.11	—	+72.68
Ag_2O(s)	231.74	−31.05	−11.20	65.86	121.3
AgBr(s)	187.77	−100.37	−96.90	52.38	107.1
AgBr(aq)	187.77	−15.98	−26.86	—	155.2
AgCl(s)	143.32	−127.07	−109.79	50.79	96.2
AgCl(aq)	143.32	−61.58	−54.12	—	129.3
AgI(s)	234.77	−61.84	−66.19	56.82	115.5
AgI(aq)	234.77	+50.38	+25.52	—	184.1
$AgNO_3$(s)	169.88	−124.39	−33.41	93.05	140.92
Sodium					
Na(s)	22.99	0	0	28.24	51.21
Na(g)	22.99	+107.32	+76.76	20.79	153.71
Na^+(aq)	22.99	−240.12	−261.91	—	+59.0
NaOH(s)	40.00	−425.61	−379.49	59.54	64.46
NaOH(aq)	40.00	−470.11	−419.15	—	48.1
NaCl(s)	58.44	−411.15	−384.14	50.50	72.13
NaBr(s)	102.89	−361.06	−348.98	51.38	86.82
NaI(s)	149.89	−287.78	−286.06	52.09	98.53
Sulfur					
S(s), rhombic	32.06	0	0	22.64	31.80
S(s), monoclinic	32.06	+0.33	+0.1	23.6	32.6
S^{2-}(aq)	32.06	+33.1	+85.8	—	−14.6
SO_2(g)	64.06	−296.83	−300.19	39.87	248.22
SO_3(g)	80.06	−395.72	−371.06	50.67	256.76

(continued)

Inorganic Substances *(continued)*

Substance	Molar mass, M (g·mol^{-1})	Enthalpy of formation, $\Delta H_f°$ (kJ·mol^{-1})	Free energy of formation, $\Delta G_f°$ (kJ·mol^{-1})	Molar heat capacity, $C_{P,m}$ (J·K^{-1}·mol^{-1})	Molar entropy,* $S_m°$ (J·K^{-1}·mol^{-1})
$H_2SO_4(l)$	98.08	−813.99	−690.00	138.9	156.90
$SO_4^{2-}(aq)$	96.06	−909.27	−744.53	—	+20.1
$HSO_4^-(aq)$	97.07	−887.34	−755.91	—	+131.8
$H_2S(g)$	34.08	−20.63	−33.56	34.23	205.79
$H_2S(aq)$	34.08	−39.7	−27.83	—	121
$SF_6(g)$	146.06	−1209	−1105.3	97.28	291.82
Tin					
Sn(s), white	118.71	0	0	26.99	51.55
Sn(s), gray	118.71	−2.09	+0.13	25.77	44.14
SnO(s)	134.71	−285.8	−256.9	44.31	56.5
$SnO_2(s)$	150.71	−580.7	−519.6	52.59	52.3
Zinc					
Zn(s)	65.41	0	0	25.40	41.63
$Zn^{2+}(aq)$	65.41	−153.89	−147.06	—	−112.1
ZnO(s)	81.41	−348.28	−318.30	40.25	43.64

*The entropies of individual ions in solution are determined by setting the entropy of H^+ in water equal to 0 and then defining the entropies of all other ions relative to this value; hence a negative entropy is one that is lower than the entropy of H^+ in water. All *absolute* entropies are positive, and no sign need be given; all entropies of ions are relative to that of H^+ and are listed here with a sign (either + or −).

Organic Compounds

Substance	Molar mass, M (g·mol^{-1})	Enthalpy of combustion, $\Delta H_c°$ (kJ·mol^{-1})	Enthalpy of formation, $\Delta H_f°$ (kJ·mol^{-1})	Free energy of formation, $\Delta G_f°$ (kJ·mol^{-1})	Molar heat capacity, $C_{P,m}$ (J·K^{-1}·mol^{-1})	Molar entropy, $S°$ (J·K^{-1}·mol^{-1})
Hydrocarbons						
$CH_4(g)$, methane	16.04	−890	−74.81	−50.72	35.31	186.26
$C_2H_2(g)$, ethyne (acetylene)	26.04	−1300	+226.73	+209.20	43.93	200.94
$C_2H_4(g)$, ethene (ethylene)	28.05	−1411	+52.26	+68.15	43.56	219.56
$C_2H_6(g)$, ethane	30.07	−1560	−84.68	−32.82	52.63	229.60
$C_3H_6(g)$, propene (propylene)	42.08	−2058	+20.42	+62.78	63.89	266.6
$C_3H_6(g)$, cyclopropane	42.08	−2091	+53.30	+104.45	55.94	237.4
$C_3H_8(g)$, propane	44.09	−2220	−103.85	−23.49	73.5	270.2
$C_4H_{10}(g)$, butane	58.12	−2878	−126.15	−17.03	97.45	310.1

Organic Compounds *(continued)*

Substance	Molar mass, M ($g \cdot mol^{-1}$)	Enthalpy of combustion, ΔH_c° ($kJ \cdot mol^{-1}$)	Enthalpy of formation, ΔH_f° ($kJ \cdot mol^{-1}$)	Free energy of formation, ΔG_f° ($kJ \cdot mol^{-1}$)	Molar heat capacity, $C_{P,m}$ ($J \cdot K^{-1} \cdot mol^{-1}$)	Molar entropy, S° ($J \cdot K^{-1} \cdot mol^{-1}$)
C_5H_{12}(g), pentane	72.14	−3537	−146.44	−8.20	120.2	349
C_6H_6(l), benzene	78.11	−3268	+49.0	+124.3	136.1	173.3
C_6H_6(g)	78.11	−3302	+82.9	+129.72	81.67	269.31
C_7H_8(l), toluene	92.13	−3910	+12.0	+113.8	—	221.0
C_7H_8(g)	92.13	−3953	+50.0	+122.0	103.6	320.7
C_6H_{12}(l), cyclohexane	84.15	−3920	−156.4	+26.7	156.5	204.4
C_6H_{12}(g)	84.15	−3953	—	—	—	—
C_8H_{18}(l), octane	114.22	−5471	−249.9	+6.4	—	358
Alcohols and phenols						
CH_3OH(l), methanol	32.04	−726	−238.86	−166.27	81.6	126.8
CH_3OH(g)	32.04	−764	−200.66	−161.96	43.89	239.81
C_2H_5OH(l), ethanol	46.07	−1368	−277.69	−174.78	111.46	160.7
C_2H_5OH(g)	46.07	−1409	−235.10	−168.49	65.44	282.70
C_6H_5OH(s), phenol	94.11	−3054	−164.6	−50.42	—	144.0
Carboxylic acids						
HCOOH(l), formic acid	46.02	−255	−424.72	−361.35	99.04	128.95
CH_3COOH(l), acetic acid	60.05	−875	−484.5	−389.9	124.3	159.8
CH_3COOH(aq)	60.05	—	−485.76	−396.46	—	86.6
$(COOH)_2$(s), oxalic acid	90.04	−254	−827.2	−697.9	117	120
C_6H_5COOH(s), benzoic acid	122.12	−3227	−385.1	−245.3	146.8	167.6
Aldehydes and ketones						
HCHO(g), methanal (formaldehyde)	30.03	−571	−108.57	−102.53	35.40	218.77
CH_3CHO(l), ethanal (acetaldehyde)	44.05	−1166	−192.30	−128.12	—	160.2
CH_3CHO(g)	44.05	−1192	−166.19	−128.86	57.3	250.3
CH_3COCH_3(l), propanone (acetone)	58.08	−1790	−248.1	−155.4	124.7	200
Sugars						
$C_6H_{12}O_6$(s), glucose	180.15	−2808	−1268	−910	—	212
$C_6H_{12}O_6$(aq)	180.15	—	—	−917	—	—
$C_6H_{12}O_6$(s), fructose	180.15	−2810	−1266	—	—	—
$C_{12}H_{22}O_{11}$(s), sucrose	342.29	−5645	−2222	−1545	—	360
Nitrogen compounds						
$CO(NH_2)_2$(s), urea	60.06	−632	−333.51	−197.33	93.14	104.60
$C_6H_5NH_2$(l), aniline	93.13	−3393	+31.6	+149.1	—	191.3
NH_2CH_2COOH(s), glycine	75.07	−969	−532.9	−373.4	99.2	103.51
CH_3NH_2(g), methylamine	31.06	−1085	−22.97	+32.16	53.1	243.41