APPENDIX D

Thermodynamic Data

Standard molar entropies, enthalpies of formation, Gibbs energies of formation, and heat capacities of various substances at 25°C and 1 bar*

Substance	$S°$/J·K^{-1}·mol^{-1}†	$\Delta H_f°$/kJ·mol^{-1}	$\Delta G_f°$/kJ·mol^{-1}	C_p/J·K^{-1}·mol^{-1}
aluminum				
$Al(s)$	28.3	0	0	24.4
$Al_2O_3(s)$	50.9	−1675.7	−1582.3	79.0
argon				
$Ar(g)$	154.8	0	0	20.8
barium				
$Ba(s)$	62.5	0	0	28.1
$BaCO_3(s)$	112.1	−1213.0	−1134.4	86.0
$BaO(s)$	72.1	−548.0	−520.3	47.3
$Ba^{2+}(aq)$	9.6	−537.6	−560.8	—
bromine				
$Br(g)$	175.0	111.9	82.4	20.8
$Br_2(g)$	245.5	30.9	3.1	36.0
$Br_2(l)$	152.2	0	0	75.7
$Br^-(aq)$	82.4	−121.6	−104.0	—
calcium				
$Ca(s)$	41.6	0	0	25.9
$CaC_2(s)$	70.0	−59.8	−64.9	62.7
$CaCO_3(s)$	91.7	−1207.6	−1129.1	83.5
$CaO(s)$	38.1	−634.9	−603.3	42.0
$CaSO_4(s)$	106.5	−1434.5	−1322.0	99.7
$Ca^{2+}(aq)$	−53.1	−542.8	−553.6	—

Substance	$S°$/J·K^{-1}·mol^{-1}†	$\Delta H_f°$/kJ·mol^{-1}	$\Delta G_f°$/kJ·mol^{-1}	C_p/J·K^{-1}·mol^{-1}
carbon				
C(*s*, diamond)	2.4	1.9	2.9	6.1
C(*s*, graphite)	5.7	0	0	8.5
C_{60}(*s*, fullerene)	426.0	2327.0	2302.0	520.0
$CH_4(g)$	186.3	−74.6	−50.5	35.7
$C_2H_2(g)$	200.9	227.4	209.9	44.0
$C_2H_4(g)$	219.3	52.4	68.4	42.9
$C_2H_6(g)$	229.2	−84.0	−32.0	52.5
$C_3H_8(g)$	270.3	−103.8	−23.4	73.6
$C_6H_6(l)$	173.4	49.1	124.5	136.0
$CH_3OH(g)$	239.9	−201.0	−162.3	44.1
$CH_3OH(l)$	126.8	−239.2	−166.6	81.1
$C_2H_5OH(g)$	281.6	−234.8	−167.9	65.6
$C_2H_5OH(l)$	160.7	−277.6	−174.8	112.3
$CH_3Cl(g)$	234.6	−81.9	−58.4	40.8
$CH_3Cl(l)$	145.3	−102	−51.5	—
$CH_2Cl_2(g)$	270.2	−95.4	−68.8	51.0
$CH_2Cl_2(l)$	177.8	−124.2	−70.0	101.2
$CHCl_3(g)$	295.7	−102.7	6.0	65.7
$CHCl_3(l)$	201.7	−134.1	−73.7	114.2
$CCl_4(g)$	308.7	−95.7	−60.6	83.3
$CCl_4(l)$	215.4	−128.2	−65.3	130.7
$CO(g)$	197.7	−110.5	−137.2	29.1
$CO_2(g)$	213.8	−393.5	−394.4	37.1
$CO_3^{2-}(aq)$	−56.9	−677.1	−527.9	—
chlorine				
$Cl(g)$	165.2	121.3	105.3	21.8
$Cl_2(g)$	223.1	0	0	33.9
$Cl^-(aq)$	56.5	−167.2	−131.2	—
copper				
Cu(*s*)	33.2	0	0	24.4
CuO(*s*)	42.6	−157.3	−129.7	42.3
$Cu_2O(s)$	93.1	−168.6	−146.0	63.6
$Cu^{2+}(aq)$	−99.6	64.8	65.5	—

Substance	$S°$/J·K^{-1}·mol^{-1}†	$\Delta H_f°$/kJ·mol^{-1}	$\Delta G_f°$/kJ·mol^{-1}	C_p/J·K^{-1}·mol^{-1}
fluorine				
$F(g)$	158.8	79.4	62.3	22.7
$F_2(g)$	202.8	0	0	31.3
$F^-(aq)$	–13.8	–332.6	–278.8	—
helium				
$He(g)$	126.2	0	0	20.8
hydrogen				
$H(g)$	114.7	218.0	203.3	20.8
$H_2(g)$	130.7	0	0	28.8
$H_2O(g)$	188.8	–241.8	–228.6	33.6
$H_2O(l)$	70.0	–285.8	–237.1	75.3
$H_2O_2(l)$	109.6	–187.8	–120.4	89.1
$HF(g)$	173.8	–273.3	–275.4	29.1
$HCl(g)$	186.9	–92.3	–95.3	29.1
$HBr(g)$	198.7	–36.3	–53.4	29.1
$HI(g)$	206.6	26.5	1.7	29.2
$H_2S(g)$	205.8	–20.6	–33.4	34.2
$H^+(aq)$	0	0	0	—
$H_3O^+(aq)$	70.0	–285.8	–237.1	—
iodine				
$I(g)$	180.8	106.8	70.2	20.8
$I_2(g)$	260.7	62.4	19.3	36.9
$I_2(s)$	116.1	0	0	54.4
$I^-(aq)$	111.3	–55.2	–51.6	—
iron				
$Fe(s)$	27.3	0	0	25.1
$FeO(s)$	60.75	–272.0	–251.4	49.92
$Fe_2O_3(s)$	87.4	–824.2	–742.2	103.9
$Fe_3O_4(s)$	146.4	–1118.4	–1015.4	143.3
$Fe^{2+}(aq)$	–137.7	–89.1	–78.9	—
$Fe^{3+}(aq)$	–315.9	–48.5	–4.7	—
krypton				
$Kr(g)$	164.1	0	0	20.8

Substance	$S°$/J·K^{-1}·mol^{-1}†	$\Delta H_f°$/kJ·mol^{-1}	$\Delta G_f°$/kJ·mol^{-1}	C_p/J·K^{-1}·mol^{-1}
lead				
Pb(*s*)	64.8	0	0	26.4
$PbCl_2$(*s*)	136.0	−359.4	−314.1	—
PbO(*s*, massicot)	68.7	−217.3	−187.9	45.8
PbO(*s*, litharge)	66.5	−218.0	−188.9	45.8
$PbSO_4$(*s*)	148.5	−920.0	−813.0	103.2
Pb^{2+}(*aq*)	10.5	−1.7	−24.4	—
magnesium				
Mg(*s*)	32.7	0	0	24.9
MgO(*s*)	27.0	−601.6	−569.3	37.2
$MgCO_3$(*s*)	65.7	−1095.8	−1012.1	75.5
Mg^{2+}(*aq*)	−138.1	−466.9	−454.8	—
neon				
Ne(*g*)	146.3	0	0	20.8
nitrogen				
N(*g*)	153.3	472.7	455.5	20.8
N_2(*g*)	191.6	0	0	29.1
NH_3(*g*)	192.8	−45.9	−16.4	35.1
N_2H_4(*l*)	121.2	50.6	149.3	98.9
NO(*g*)	210.8	91.3	87.6	29.9
NO_2(*g*)	240.1	33.2	51.3	37.2
N_2O(*g*)	220.0	81.6	103.7	38.6
N_2O_4(*g*)	304.4	11.1	99.8	79.2
N_2O_4(*l*)	209.2	−19.5	97.5	142.7
N_2O_5(*s*)	178.2	−43.1	113.9	143.1
NOCl(*g*)	261.7	51.7	66.1	44.7
NH_3(*aq*)	111.3	−80.3	−26.5	—
NH_4^+(*aq*)	113.4	−132.5	−79.3	—
NO_3^-(*aq*)	146.4	−207.4	−111.3	—
oxygen				
O(*g*)	161.1	249.2	231.7	21.9
O_2(*g*)	205.2	0	0	29.4
O_3(*g*)	238.9	142.7	163.2	39.2
OH^-(*aq*)	−10.8	−230.0	−157.2	—

Substance	$S°$/J·K^{-1}·mol^{-1}†	$\Delta H_f°$/kJ·mol^{-1}	$\Delta G_f°$/kJ·mol^{-1}	C_p/J·K^{-1}·mol^{-1}
phosphorus				
P(*s*, white)	41.1	0	0	23.8
P(*s*, red)	22.8	−17.6	−12.1	21.2
$P_4O_{10}(s)$	228.9	−2984	−2698	211.7
$POCl_3(g)$	325.5	−558.5	−512.9	84.9
$POCl_3(l)$	222.5	−597.1	−520.8	138.8
$PCl_3(g)$	311.8	−287.0	−267.8	71.8
$PCl_5(g)$	364.6	−374.9	−305.0	112.8
$PH_3(g)$	210.2	5.4	13.5	37.1
potassium				
KOH(*s*)	81.2	−424.6	−379.4	68.9
KCl(*s*)	82.6	−436.5	−408.5	51.3
$KClO_3(s)$	143.1	−397.7	−296.3	100.3
$K^+(aq)$	102.5	−252.4	−283.3	—
silver				
Ag(*s*)	42.6	0	0	25.4
AgBr(*s*)	107.1	−100.4	−96.9	52.4
AgCl(*s*)	96.3	−127.0	−109.8	50.8
$Ag_2SO_4(s)$	200.4	−715.9	−618.4	131.4
$Ag^+(aq)$	72.7	105.6	77.1	—
sodium				
Na(*g*)	153.7	107.5	77.0	20.8
Na(*s*)	51.3	0	0	28.2
$NaHCO_3(s)$	101.7	−950.8	−851.0	87.6
$Na_2CO_3(s)$	135.0	−1130.7	−1044.4	112.3
$Na_2O(s)$	75.1	−414.2	−375.5	69.1
NaOH(*s*)	64.4	−425.8	−379.7	59.5
NaF(*s*)	51.1	−576.6	−546.3	46.9
NaCl(*s*)	72.1	−411.2	−384.1	50.5
NaBr(*s*)	86.8	−361.1	−349.0	51.4
NaI(*s*)	98.5	−287.8	−286.1	52.1
$Na^+(aq)$	59.0	−240.1	−261.9	—

Substance	$S°$/J·K^{-1}·mol^{-1}†	$\Delta H_f°$/kJ·mol^{-1}	$\Delta G_f°$/kJ·mol^{-1}	C_p/J·K^{-1}·mol^{-1}
sulfur				
S(*s*, rhombic)	28.5	0	0	22.6
S(*s*, monoclinic)	32.6	0.3	0.1	—
$SO_2(g)$	248.2	−296.8	−300.1	39.9
$SO_3(g)$	256.8	−395.7	−371.1	50.7
$SF_6(g)$	291.5	−1220.5	−1116.5	97.0
$SO_4^{2-}(aq)$	20.1	−909.3	−744.5	—
tin				
Sn(*s*, white)	51.2	0	0	27.0
Sn(*s*, gray)	44.1	−2.1	0.1	25.8
SnO(*s*)	57.2	−280.7	−251.9	44.3
$SnO_2(s)$	49.0	−577.6	−515.8	52.6
xenon				
Xe(*g*)	169.7	0	0	20.8
zinc				
Zn(*s*)	41.6	0	0	25.4
ZnO(*s*)	43.7	−350.5	−320.5	40.3
ZnS(*s*)	57.7	−206.0	−201.3	46.0
$Zn^{2+}(aq)$	−112.1	−153.9	−147.1	46.0

*Data from *CRC Handbook of Chemistry and Physics*, 87th online edition, 2006–2007, except where noted in blue.

†Solution-phase entropies are measured relative to a defined standard of $S°$ for $H^+(aq) \equiv 0$; thus, the given entropies of some aqueous compounds may be negative.