

# APPENDIX 3

## Thermodynamic Data at 1 atm and 25°C\*

### Inorganic Substances

Substance	$\Delta H_f^\circ$ (kJ/mol)	$\Delta G_f^\circ$ (kJ/mol)	$S^\circ$ (J/K · mol)
Ag(s)	0	0	42.7
Ag <sup>+</sup> (aq)	105.9	77.1	73.9
AgCl(s)	-127.0	-109.7	96.1
AgBr(s)	-99.5	-95.9	107.1
AgI(s)	-62.4	-66.3	114.2
AgNO <sub>3</sub> (s)	-123.1	-32.2	140.9
Al(s)	0	0	28.3
Al <sup>3+</sup> (aq)	-524.7	-481.2	-313.38
Al <sub>2</sub> O <sub>3</sub> (s)	-1669.8	-1576.4	50.99
As(s)	0	0	35.15
AsO <sub>4</sub> <sup>3-</sup> (aq)	-870.3	-635.97	-144.77
AsH <sub>3</sub> (g)	171.5		
H <sub>3</sub> AsO <sub>4</sub> (s)	-900.4		
Au(s)	0	0	47.7
Au <sub>2</sub> O <sub>3</sub> (s)	80.8	163.2	125.5
AuCl(s)	-35.2		
AuCl <sub>3</sub> (s)	-118.4		
B(s)	0	0	6.5
B <sub>2</sub> O <sub>3</sub> (s)	-1263.6	-1184.1	54.0
H <sub>3</sub> BO <sub>3</sub> (s)	-1087.9	-963.16	89.58
H <sub>3</sub> BO <sub>3</sub> (aq)	-1067.8	-963.3	159.8
Ba(s)	0	0	66.9
Ba <sup>2+</sup> (aq)	-538.4	-560.66	12.55
BaO(s)	-558.2	-528.4	70.3
BaCl <sub>2</sub> (s)	-860.1	-810.66	125.5
BaSO <sub>4</sub> (s)	-1464.4	-1353.1	132.2
BaCO <sub>3</sub> (s)	-1218.8	-1138.9	112.1
Be(s)	0	0	9.5
BeO(s)	-610.9	-581.58	14.1
Br <sub>2</sub> (l)	0	0	152.3
Br <sup>-</sup> (aq)	-120.9	-102.8	80.7
HBr(g)	-36.2	-53.2	198.48
C(graphite)	0	0	5.69
C(diamond)	1.90	2.87	2.4
CO(g)	-110.5	-137.3	197.9
CO <sub>2</sub> (g)	-393.5	-394.4	213.6
CO <sub>2</sub> (aq)	-412.9	-386.2	121.3
CO <sub>3</sub> <sup>2-</sup> (aq)	-676.3	-528.1	-53.1

\*The thermodynamic quantities of ions are based on the reference states that  $\Delta H_f^\circ[\text{H}^+(\text{aq})] = 0$ ,  $\Delta G_f^\circ[\text{H}^+(\text{aq})] = 0$ , and  $S^\circ[\text{H}^+(\text{aq})] = 0$  (see p. 807).

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Substance	$\Delta H_f^\circ$ (kJ/mol)	$\Delta G_f^\circ$ (kJ/mol)	$S^\circ$ (J/K · mol)
HCO <sub>3</sub> <sup>-</sup> (aq)	-691.1	-587.1	94.98
H <sub>2</sub> CO <sub>3</sub> (aq)	-699.7	-623.2	187.4
CS <sub>2</sub> (g)	115.3	65.1	237.8
CS <sub>2</sub> (l)	87.3	63.6	151.0
HCN(aq)	105.4	112.1	128.9
CN <sup>-</sup> (aq)	151.0	165.69	117.99
(NH <sub>2</sub> ) <sub>2</sub> CO(s)	-333.19	-197.15	104.6
(NH <sub>2</sub> ) <sub>2</sub> CO(aq)	-319.2	-203.84	173.85
Ca(s)	0	0	41.6
Ca <sup>2+</sup> (aq)	-542.96	-553.0	-55.2
CaO(s)	-635.6	-604.2	39.8
Ca(OH) <sub>2</sub> (s)	-986.6	-896.8	83.4
CaF <sub>2</sub> (s)	-1214.6	-1161.9	68.87
CaCl <sub>2</sub> (s)	-794.96	-750.19	113.8
CaSO <sub>4</sub> (s)	-1432.69	-1320.3	106.69
CaCO <sub>3</sub> (s)	-1206.9	-1128.8	92.9
Cd(s)	0	0	51.46
Cd <sup>2+</sup> (aq)	-72.38	-77.7	-61.09
CdO(s)	-254.6	-225.06	54.8
CdCl <sub>2</sub> (s)	-389.1	-342.59	118.4
CdSO <sub>4</sub> (s)	-926.17	-820.2	137.2
Cl <sub>2</sub> (g)	0	0	223.0
Cl <sup>-</sup> (aq)	-167.2	-131.2	56.5
HCl(g)	-92.3	-95.27	187.0
Co(s)	0	0	28.45
Co <sup>2+</sup> (aq)	-67.36	-51.46	155.2
CoO(s)	-239.3	-213.38	43.9
Cr(s)	0	0	23.77
Cr <sup>2+</sup> (aq)	-138.9		
Cr <sub>2</sub> O <sub>3</sub> (s)	-1128.4	-1046.8	81.17
CrO <sub>4</sub> <sup>2-</sup> (aq)	-863.16	-706.26	38.49
Cr <sub>2</sub> O <sub>7</sub> <sup>2-</sup> (aq)	-1460.6	-1257.29	213.8
Cs(s)	0	0	82.8
Cs <sup>+</sup> (aq)	-247.69	-282.0	133.05
Cu(s)	0	0	33.3
Cu <sup>+</sup> (aq)	51.88	50.2	-26.4
Cu <sup>2+</sup> (aq)	64.39	64.98	-99.6
CuO(s)	-155.2	-127.2	43.5
Cu <sub>2</sub> O(s)	-166.69	-146.36	100.8
CuCl(s)	-134.7	-118.8	91.6
CuCl <sub>2</sub> (s)	-205.85	?	?
CuS(s)	-48.5	-49.0	66.5
CuSO <sub>4</sub> (s)	-769.86	-661.9	113.39
F <sub>2</sub> (g)	0	0	203.34
F <sup>-</sup> (aq)	-329.1	-276.48	-9.6
HF(g)	-271.6	-270.7	173.5
Fe(s)	0	0	27.2
Fe <sup>2+</sup> (aq)	-87.86	-84.9	-113.39

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Substance	$\Delta H_f^\circ$ (kJ/mol)	$\Delta G_f^\circ$ (kJ/mol)	$S^\circ$ (J/K · mol)
Fe <sup>3+</sup> (aq)	-47.7	-10.5	-293.3
FeO(s)	-272.0	-255.2	60.8
Fe <sub>2</sub> O <sub>3</sub> (s)	-822.2	-741.0	90.0
Fe(OH) <sub>2</sub> (s)	-568.19	-483.55	79.5
Fe(OH) <sub>3</sub> (s)	-824.25	?	?
H(g)	218.2	203.2	114.6
H <sub>2</sub> (g)	0	0	131.0
H <sup>+</sup> (aq)	0	0	0
OH <sup>-</sup> (aq)	-229.94	-157.30	-10.5
H <sub>2</sub> O(g)	-241.8	-228.6	188.7
H <sub>2</sub> O(l)	-285.8	-237.2	69.9
H <sub>2</sub> O <sub>2</sub> (l)	-187.6	-118.1	?
Hg(l)	0	0	77.4
Hg <sup>2+</sup> (aq)		-164.38	
HgO(s)	-90.7	-58.5	72.0
HgCl <sub>2</sub> (s)	-230.1		
Hg <sub>2</sub> Cl <sub>2</sub> (s)	-264.9	-210.66	196.2
HgS(s)	-58.16	-48.8	77.8
HgSO <sub>4</sub> (s)	-704.17		
Hg <sub>2</sub> SO <sub>4</sub> (s)	-741.99	-623.92	200.75
I <sub>2</sub> (s)	0	0	116.7
I <sup>-</sup> (aq)	-55.9	-51.67	109.37
HI(g)	25.9	1.30	206.3
K(s)	0	0	63.6
K <sup>+</sup> (aq)	-251.2	-282.28	102.5
KOH(s)	-425.85		
KCl(s)	-435.87	-408.3	82.68
KClO <sub>3</sub> (s)	-391.20	-289.9	142.97
KClO <sub>4</sub> (s)	-433.46	-304.18	151.0
KBr(s)	-392.17	-379.2	96.4
KI(s)	-327.65	-322.29	104.35
KNO <sub>3</sub> (s)	-492.7	-393.1	132.9
Li(s)	0	0	28.0
Li <sup>+</sup> (aq)	-278.46	-293.8	14.2
Li <sub>2</sub> O(s)	-595.8	?	?
LiOH(s)	-487.2	-443.9	50.2
Mg(s)	0	0	32.5
Mg <sup>2+</sup> (aq)	-461.96	-456.0	-117.99
MgO(s)	-601.8	-569.6	26.78
Mg(OH) <sub>2</sub> (s)	-924.66	-833.75	63.1
MgCl <sub>2</sub> (s)	-641.8	-592.3	89.5
MgSO <sub>4</sub> (s)	-1278.2	-1173.6	91.6
MgCO <sub>3</sub> (s)	-1112.9	-1029.3	65.69
Mn(s)	0	0	31.76
Mn <sup>2+</sup> (aq)	-218.8	-223.4	-83.68
MnO <sub>2</sub> (s)	-520.9	-466.1	53.1
N <sub>2</sub> (g)	0	0	191.5
N <sub>3</sub> <sup>-</sup> (aq)	245.18	?	?

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Substance	$\Delta H_f^\circ$ (kJ/mol)	$\Delta G_f^\circ$ (kJ/mol)	$S^\circ$ (J/K · mol)
NH <sub>3</sub> (g)	-46.3	-16.6	193.0
NH <sub>4</sub> <sup>+</sup> (aq)	-132.80	-79.5	112.8
NH <sub>4</sub> Cl(s)	-315.39	-203.89	94.56
NH <sub>3</sub> (aq)	-80.3	-26.5	111.3
N <sub>2</sub> H <sub>4</sub> (l)	50.4		
NO(g)	90.4	86.7	210.6
NO <sub>2</sub> (g)	33.85	51.8	240.46
N <sub>2</sub> O <sub>4</sub> (g)	9.66	98.29	304.3
N <sub>2</sub> O(g)	81.56	103.6	219.99
HNO <sub>2</sub> (aq)	-118.8	-53.6	
HNO <sub>3</sub> (l)	-173.2	-79.9	155.6
NO <sub>3</sub> <sup>-</sup> (aq)	-206.57	-110.5	146.4
Na(s)	0	0	51.05
Na <sup>+</sup> (aq)	-239.66	-261.87	60.25
Na <sub>2</sub> O(s)	-415.9	-376.56	72.8
NaCl(s)	-411.0	-384.0	72.38
NaI(s)	-288.0		
Na <sub>2</sub> SO <sub>4</sub> (s)	-1384.49	-1266.8	149.49
NaNO <sub>3</sub> (s)	-466.68	-365.89	116.3
Na <sub>2</sub> CO <sub>3</sub> (s)	-1130.9	-1047.67	135.98
NaHCO <sub>3</sub> (s)	-947.68	-851.86	102.09
Ni(s)	0	0	30.1
Ni <sup>2+</sup> (aq)	-64.0	-46.4	-159.4
NiO(s)	-244.35	-216.3	38.58
Ni(OH) <sub>2</sub> (s)	-538.06	-453.1	79.5
O(g)	249.4	230.1	160.95
O <sub>2</sub> (g)	0	0	205.0
O <sub>3</sub> (aq)	-12.09	16.3	110.88
O <sub>3</sub> (g)	142.2	163.4	237.6
P(white)	0	0	44.0
P(red)	-18.4	13.8	29.3
PO <sub>4</sub> <sup>3-</sup> (aq)	-1284.07	-1025.59	-217.57
P <sub>4</sub> O <sub>10</sub> (s)	-3012.48		
PH <sub>3</sub> (g)	9.25	18.2	210.0
HPO <sub>4</sub> <sup>2-</sup> (aq)	-1298.7	-1094.1	-35.98
H <sub>2</sub> PO <sub>4</sub> <sup>-</sup> (aq)	-1302.48	-1135.1	89.1
Pb(s)	0	0	64.89
Pb <sup>2+</sup> (aq)	1.6	-24.3	21.3
PbO(s)	-217.86	-188.49	69.45
PbO <sub>2</sub> (s)	-276.65	-218.99	76.57
PbCl <sub>2</sub> (s)	-359.2	-313.97	136.4
PbS(s)	-94.3	-92.68	91.2
PbSO <sub>4</sub> (s)	-918.4	-811.2	147.28
Pt(s)	0	0	41.84
PtCl <sub>4</sub> <sup>2-</sup> (aq)	-516.3	-384.5	175.7
Rb(s)	0	0	69.45
Rb <sup>+</sup> (aq)	-246.4	-282.2	124.27
S(rhombic)	0	0	31.88

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Substance	$\Delta H_f^\circ$ (kJ/mol)	$\Delta G_f^\circ$ (kJ/mol)	$S^\circ$ (J/K · mol)
S(monoclinic)	0.30	0.10	32.55
SO <sub>2</sub> (g)	-296.4	-300.4	248.5
SO <sub>3</sub> (g)	-395.2	-370.4	256.2
SO <sub>3</sub> <sup>2-</sup> (aq)	-624.25	-497.06	43.5
SO <sub>4</sub> <sup>2-</sup> (aq)	-907.5	-741.99	17.15
H <sub>2</sub> S(g)	-20.15	-33.0	205.64
HSO <sub>3</sub> <sup>-</sup> (aq)	-627.98	-527.3	132.38
HSO <sub>4</sub> <sup>-</sup> (aq)	-885.75	-752.87	126.86
H <sub>2</sub> SO <sub>4</sub> (l)	-811.3	?	?
SF <sub>6</sub> (g)	-1096.2	?	?
Si(s)	0	0	18.70
SiO <sub>2</sub> (s)	-859.3	-805.0	41.84
Sr(s)	0	0	54.39
Sr <sup>2+</sup> (aq)	-545.5	-557.3	-39.33
SrCl <sub>2</sub> (s)	-828.4	-781.15	117.15
SrSO <sub>4</sub> (s)	-1444.74	-1334.28	121.75
SrCO <sub>3</sub> (s)	-1218.38	-1137.6	97.07
Zn(s)	0	0	41.6
Zn <sup>2+</sup> (aq)	-152.4	-147.2	-106.48
ZnO(s)	-348.0	-318.2	43.9
ZnCl <sub>2</sub> (s)	-415.89	-369.26	108.37
ZnS(s)	-202.9	-198.3	57.7
ZnSO <sub>4</sub> (s)	-978.6	-871.6	124.7

### Organic Substances

Substance	Formula	$\Delta H_f^\circ$ (kJ/mol)	$\Delta G_f^\circ$ (kJ/mol)	$S^\circ$ (J/K · mol)
Acetic acid(l)	CH <sub>3</sub> COOH	-484.2	-389.45	159.8
Acetaldehyde(g)	CH <sub>3</sub> CHO	-166.35	-139.08	264.2
Acetone(l)	CH <sub>3</sub> COCH <sub>3</sub>	-246.8	-153.55	198.7
Acetylene(g)	C <sub>2</sub> H <sub>2</sub>	226.6	209.2	200.8
Benzene(l)	C <sub>6</sub> H <sub>6</sub>	49.04	124.5	172.8
Butane(g)	C <sub>4</sub> H <sub>10</sub>	-124.7	-15.7	310.0
Ethanol(l)	C <sub>2</sub> H <sub>5</sub> OH	-276.98	-174.18	161.0
Ethane(g)	C <sub>2</sub> H <sub>6</sub>	-84.7	-32.89	229.5
Ethylene(g)	C <sub>2</sub> H <sub>4</sub>	52.3	68.1	219.5
Formic acid(l)	HCOOH	-409.2	-346.0	129.0
Glucose(s)	C <sub>6</sub> H <sub>12</sub> O <sub>6</sub>	-1274.5	-910.56	212.1
Methane(g)	CH <sub>4</sub>	-74.85	-50.8	186.2
Methanol(l)	CH <sub>3</sub> OH	-238.7	-166.3	126.8
Propane(g)	C <sub>3</sub> H <sub>8</sub>	-103.9	-23.5	269.9
Sucrose(s)	C <sub>12</sub> H <sub>22</sub> O <sub>11</sub>	-2221.7	-1544.3	360.2