

Appendix G

Standard Thermodynamic Properties For Selected Substances

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Substance	ΔH_f° (kJ mol ⁻¹)	ΔG_f° (kJ mol ⁻¹)	S° (J K ⁻¹ mol ⁻¹)
aluminum			
Al(s)	0	0	28.3
Al(g)	324.4	285.7	164.54
Al ³⁺ (aq)	-531	-485	-321.7
Al ₂ O ₃ (s)	-1676	-1582	50.92
AlF ₃ (s)	-1510.4	-1425	66.5
AlCl ₃ (s)	-704.2	-628.8	110.67
AlCl ₃ ·6H ₂ O(s)	-2691.57	-2269.40	376.56
Al ₂ S ₃ (s)	-724.0	-492.4	116.9
Al ₂ (SO ₄) ₃ (s)	-3445.06	-3506.61	239.32
antimony			
Sb(s)	0	0	45.69
Sb(g)	262.34	222.17	180.16
Sb ₄ O ₆ (s)	-1440.55	-1268.17	220.92
SbCl ₃ (g)	-313.8	-301.2	337.80
SbCl ₅ (g)	-394.34	-334.29	401.94
Sb ₂ S ₃ (s)	-174.89	-173.64	182.00
SbCl ₃ (s)	-382.17	-323.72	184.10
SbOCl(s)	-374.0	—	—
arsenic			
As(s)	0	0	35.1
As(g)	302.5	261.0	174.21
As ₄ (g)	143.9	92.4	314
As ₄ O ₆ (s)	-1313.94	-1152.52	214.22
As ₂ O ₅ (s)	-924.87	-782.41	105.44

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Substance	ΔH_f° (kJ mol ⁻¹)	ΔG_f° (kJ mol ⁻¹)	S° (J K ⁻¹ mol ⁻¹)
AsCl ₃ (g)	-261.50	-248.95	327.06
As ₂ S ₃ (s)	-169.03	-168.62	163.59
AsH ₃ (g)	66.44	68.93	222.78
H ₃ AsO ₄ (s)	-906.3	—	—
barium			
Ba(s)	0	0	62.5
Ba(g)	180	146	170.24
Ba ²⁺ (aq)	-537.6	-560.8	9.6
BaO(s)	-548.0	-520.3	72.1
BaCl ₂ (s)	-855.0	-806.7	123.7
BaSO ₄ (s)	-1473.2	-1362.3	132.2
beryllium			
Be(s)	0	0	9.50
Be(g)	324.3	286.6	136.27
BeO(s)	-609.4	-580.1	13.8
bismuth			
Bi(s)	0	0	56.74
Bi(g)	207.1	168.2	187.00
Bi ₂ O ₃ (s)	-573.88	-493.7	151.5
BiCl ₃ (s)	-379.07	-315.06	176.98
Bi ₂ S ₃ (s)	-143.1	-140.6	200.4
boron			
B(s)	0	0	5.86
B(g)	565.0	521.0	153.4
B ₂ O ₃ (s)	-1273.5	-1194.3	53.97
B ₂ H ₆ (g)	36.4	87.6	232.1
H ₃ BO ₃ (s)	-1094.33	-968.92	88.83
BF ₃ (g)	-1136.0	-1119.4	254.4
BCl ₃ (g)	-403.8	-388.7	290.1
B ₃ N ₃ H ₆ (l)	-540.99	-392.79	199.58
HBO ₂ (s)	-794.25	-723.41	37.66

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Substance	ΔH_f° (kJ mol ⁻¹)	ΔG_f° (kJ mol ⁻¹)	S° (J K ⁻¹ mol ⁻¹)
bromine			
Br ₂ (l)	0	0	152.23
Br ₂ (g)	30.91	3.142	245.5
Br(g)	111.88	82.429	175.0
Br ⁻ (aq)	-120.9	-102.82	80.71
BrF ₃ (g)	-255.60	-229.45	292.42
HBr(g)	-36.3	-53.43	198.7
cadmium			
Cd(s)	0	0	51.76
Cd(g)	112.01	77.41	167.75
Cd ²⁺ (aq)	-75.90	-77.61	-73.2
CdO(s)	-258.2	-228.4	54.8
CdCl ₂ (s)	-391.5	-343.9	115.3
CdSO ₄ (s)	-933.3	-822.7	123.0
CdS(s)	-161.9	-156.5	64.9
calcium			
Ca(s)	0	0	41.6
Ca(g)	178.2	144.3	154.88
Ca ²⁺ (aq)	-542.96	-553.04	-55.2
CaO(s)	-634.9	-603.3	38.1
Ca(OH) ₂ (s)	-985.2	-897.5	83.4
CaSO ₄ (s)	-1434.5	-1322.0	106.5
CaSO ₄ ·2H ₂ O(s)	-2022.63	-1797.45	194.14
CaCO ₃ (s) (calcite)	-1220.0	-1081.4	110.0
CaSO ₃ ·H ₂ O(s)	-1752.68	-1555.19	184.10
carbon			
C(s) (graphite)	0	0	5.740
C(s) (diamond)	1.89	2.90	2.38
C(g)	716.681	671.2	158.1
CO(g)	-110.52	-137.15	197.7
CO ₂ (g)	-393.51	-394.36	213.8

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Substance	ΔH_f° (kJ mol ⁻¹)	ΔG_f° (kJ mol ⁻¹)	S° (J K ⁻¹ mol ⁻¹)
CO ₃ ²⁻ (aq)	-677.1	-527.8	-56.9
CH ₄ (g)	-74.6	-50.5	186.3
CH ₃ OH(l)	-239.2	-166.6	126.8
CH ₃ OH(g)	-201.0	-162.3	239.9
CCl ₄ (l)	-128.2	-62.5	214.4
CCl ₄ (g)	-95.7	-58.2	309.7
CHCl ₃ (l)	-134.1	-73.7	201.7
CHCl ₃ (g)	-103.14	-70.34	295.71
CS ₂ (l)	89.70	65.27	151.34
CS ₂ (g)	116.9	66.8	238.0
C ₂ H ₂ (g)	227.4	209.2	200.9
C ₂ H ₄ (g)	52.4	68.4	219.3
C ₂ H ₆ (g)	-84.0	-32.0	229.2
CH ₃ CO ₂ H(l)	-484.3	-389.9	159.8
CH ₃ CO ₂ H(g)	-434.84	-376.69	282.50
C ₂ H ₅ OH(l)	-277.6	-174.8	160.7
C ₂ H ₅ OH(g)	-234.8	-167.9	281.6
HCO ₃ ⁻ (aq)	-691.11	-587.06	95
C ₃ H ₈ (g)	-103.8	-23.4	270.3
C ₆ H ₆ (g)	82.927	129.66	269.2
C ₆ H ₆ (l)	49.1	124.50	173.4
CH ₂ Cl ₂ (l)	-124.2	-63.2	177.8
CH ₂ Cl ₂ (g)	-95.4	-65.90	270.2
CH ₃ Cl(g)	-81.9	-60.2	234.6
C ₂ H ₅ Cl(l)	-136.52	-59.31	190.79
C ₂ H ₅ Cl(g)	-112.17	-60.39	276.00
C ₂ N ₂ (g)	308.98	297.36	241.90
HCN(l)	108.9	125.0	112.8
HCN(g)	135.5	124.7	201.8
cesium			
Cs ⁺ (aq)	-248	-282.0	133

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Substance	ΔH_f° (kJ mol ⁻¹)	ΔG_f° (kJ mol ⁻¹)	S° (J K ⁻¹ mol ⁻¹)
chlorine			
Cl ₂ (g)	0	0	223.1
Cl(g)	121.3	105.70	165.2
Cl ⁻ (aq)	-167.2	-131.2	56.5
ClF(g)	-54.48	-55.94	217.78
ClF ₃ (g)	-158.99	-118.83	281.50
Cl ₂ O(g)	80.3	97.9	266.2
Cl ₂ O ₇ (l)	238.1	—	—
Cl ₂ O ₇ (g)	272.0	—	—
HCl(g)	-92.307	-95.299	186.9
HClO ₄ (l)	-40.58	—	—
chromium			
Cr(s)	0	0	23.77
Cr(g)	396.6	351.8	174.50
CrO ₄ ²⁻ (aq)	-881.2	-727.8	50.21
Cr ₂ O ₇ ²⁻ (aq)	-1490.3	-1301.1	261.9
Cr ₂ O ₃ (s)	-1139.7	-1058.1	81.2
CrO ₃ (s)	-589.5	—	—
(NH ₄) ₂ Cr ₂ O ₇ (s)	-1806.7	—	—
cobalt			
Co(s)	0	0	30.0
Co ²⁺ (aq)	-67.4	-51.5	-155
Co ³⁺ (aq)	92	134	-305.0
CoO(s)	-237.9	-214.2	52.97
Co ₃ O ₄ (s)	-910.02	-794.98	114.22
Co(NO ₃) ₂ (s)	-420.5	—	—
copper			
Cu(s)	0	0	33.15
Cu(g)	338.32	298.58	166.38
Cu ⁺ (aq)	51.9	50.2	-26
Cu ²⁺ (aq)	64.77	65.49	-99.6

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Substance	ΔH_f° (kJ mol ⁻¹)	ΔG_f° (kJ mol ⁻¹)	S° (J K ⁻¹ mol ⁻¹)
CuO(s)	-157.3	-129.7	42.63
Cu ₂ O(s)	-168.6	-146.0	93.14
CuS(s)	-53.1	-53.6	66.5
Cu ₂ S(s)	-79.5	-86.2	120.9
CuSO ₄ (s)	-771.36	-662.2	109.2
Cu(NO ₃) ₂ (s)	-302.9	—	—
fluorine			
F ₂ (g)	0	0	202.8
F(g)	79.4	62.3	158.8
F ⁻ (aq)	-332.6	-278.8	-13.8
F ₂ O(g)	24.7	41.9	247.43
HF(g)	-273.3	-275.4	173.8
hydrogen			
H ₂ (g)	0	0	130.7
H(g)	217.97	203.26	114.7
H ⁺ (aq)	0	0	0
OH ⁻ (aq)	-230.0	-157.2	-10.75
H ₃ O ⁺ (aq)	-285.8		69.91
H ₂ O(l)	-285.83	-237.1	70.0
H ₂ O(g)	-241.82	-228.59	188.8
H ₂ O ₂ (l)	-187.78	-120.35	109.6
H ₂ O ₂ (g)	-136.3	-105.6	232.7
HF(g)	-273.3	-275.4	173.8
HCl(g)	-92.307	-95.299	186.9
HBr(g)	-36.3	-53.43	198.7
HI(g)	26.48	1.70	206.59
H ₂ S(g)	-20.6	-33.4	205.8
H ₂ Se(g)	29.7	15.9	219.0
iodine			
I ₂ (s)	0	0	116.14
I ₂ (g)	62.438	19.3	260.7

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Substance	ΔH_f° (kJ mol ⁻¹)	ΔG_f° (kJ mol ⁻¹)	S° (J K ⁻¹ mol ⁻¹)
I(g)	106.84	70.2	180.8
I ⁻ (aq)	-55.19	-51.57	11.13
IF(g)	95.65	-118.49	236.06
ICl(g)	17.78	-5.44	247.44
IBr(g)	40.84	3.72	258.66
IF ₇ (g)	-943.91	-818.39	346.44
HI(g)	26.48	1.70	206.59
iron			
Fe(s)	0	0	27.3
Fe(g)	416.3	370.7	180.5
Fe ²⁺ (aq)	-89.1	-78.90	-137.7
Fe ³⁺ (aq)	-48.5	-4.7	-315.9
Fe ₂ O ₃ (s)	-824.2	-742.2	87.40
Fe ₃ O ₄ (s)	-1118.4	-1015.4	146.4
Fe(CO) ₅ (l)	-774.04	-705.42	338.07
Fe(CO) ₅ (g)	-733.87	-697.26	445.18
FeCl ₂ (s)	-341.79	-302.30	117.95
FeCl ₃ (s)	-399.49	-334.00	142.3
FeO(s)	-272.0	-255.2	60.75
Fe(OH) ₂ (s)	-569.0	-486.5	88.
Fe(OH) ₃ (s)	-823.0	-696.5	106.7
FeS(s)	-100.0	-100.4	60.29
Fe ₃ C(s)	25.10	20.08	104.60
lead			
Pb(s)	0	0	64.81
Pb(g)	195.2	162.	175.4
Pb ²⁺ (aq)	-1.7	-24.43	10.5
PbO(s) (yellow)	-217.32	-187.89	68.70
PbO(s) (red)	-218.99	-188.93	66.5
Pb(OH) ₂ (s)	-515.9	—	—
PbS(s)	-100.4	-98.7	91.2

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Substance	ΔH_f° (kJ mol ⁻¹)	ΔG_f° (kJ mol ⁻¹)	S° (J K ⁻¹ mol ⁻¹)
Pb(NO ₃) ₂ (s)	-451.9	—	—
PbO ₂ (s)	-277.4	-217.3	68.6
PbCl ₂ (s)	-359.4	-314.1	136.0
lithium			
Li(s)	0	0	29.1
Li(g)	159.3	126.6	138.8
Li ⁺ (aq)	-278.5	-293.3	13.4
LiH(s)	-90.5	-68.3	20.0
Li(OH)(s)	-487.5	-441.5	42.8
LiF(s)	-616.0	-587.5	35.7
Li ₂ CO ₃ (s)	-1216.04	-1132.19	90.17
magnesium			
Mg ²⁺ (aq)	-466.9	-454.8	-138.1
manganese			
Mn(s)	0	0	32.0
Mn(g)	280.7	238.5	173.7
Mn ²⁺ (aq)	-220.8	-228.1	-73.6
MnO(s)	-385.2	-362.9	59.71
MnO ₂ (s)	-520.03	-465.1	53.05
Mn ₂ O ₃ (s)	-958.97	-881.15	110.46
Mn ₃ O ₄ (s)	-1378.83	-1283.23	155.64
MnO ₄ ⁻ (aq)	-541.4	-447.2	191.2
MnO ₄ ²⁻ (aq)	-653.0	-500.7	59
mercury			
Hg(l)	0	0	75.9
Hg(g)	61.4	31.8	175.0
Hg ²⁺ (aq)		164.8	
Hg ²⁺ (aq)	172.4	153.9	84.5
HgO(s) (red)	-90.83	-58.5	70.29
HgO(s) (yellow)	-90.46	-58.43	71.13
HgCl ₂ (s)	-224.3	-178.6	146.0

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Substance	ΔH_f° (kJ mol ⁻¹)	ΔG_f° (kJ mol ⁻¹)	S° (J K ⁻¹ mol ⁻¹)
Hg ₂ Cl ₂ (s)	-265.4	-210.7	191.6
HgS(s) (red)	-58.16	-50.6	82.4
HgS(s) (black)	-53.56	-47.70	88.28
HgSO ₄ (s)	-707.51	-594.13	0.00
nickel			
Ni ²⁺ (aq)	-64.0	-46.4	-159
nitrogen			
N ₂ (g)	0	0	191.6
N(g)	472.704	455.5	153.3
NO(g)	90.25	87.6	210.8
NO ₂ (g)	33.2	51.30	240.1
N ₂ O(g)	81.6	103.7	220.0
N ₂ O ₃ (g)	83.72	139.41	312.17
NO ₃ ⁻ (aq)	-205.0	-108.7	146.4
N ₂ O ₄ (g)	11.1	99.8	304.4
N ₂ O ₅ (g)	11.3	115.1	355.7
NH ₃ (g)	-45.9	-16.5	192.8
NH ₄ ⁺ (aq)	-132.5	-79.31	113.4
N ₂ H ₄ (l)	50.63	149.43	121.21
N ₂ H ₄ (g)	95.4	159.4	238.5
NH ₄ NO ₃ (s)	-365.56	-183.87	151.08
NH ₄ Cl(s)	-314.43	-202.87	94.6
NH ₄ Br(s)	-270.8	-175.2	113.0
NH ₄ I(s)	-201.4	-112.5	117.0
NH ₄ NO ₂ (s)	-256.5	—	—
HNO ₃ (l)	-174.1	-80.7	155.6
HNO ₃ (g)	-133.9	-73.5	266.9
oxygen			
O ₂ (g)	0	0	205.2
O(g)	249.17	231.7	161.1
O ₃ (g)	142.7	163.2	238.9

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Substance	ΔH_f° (kJ mol ⁻¹)	ΔG_f° (kJ mol ⁻¹)	S° (J K ⁻¹ mol ⁻¹)
phosphorus			
P ₄ (s)	0	0	164.4
P ₄ (g)	58.91	24.4	280.0
P(g)	314.64	278.25	163.19
PH ₃ (g)	5.4	13.5	210.2
PCl ₃ (g)	-287.0	-267.8	311.78
PCl ₅ (g)	-374.9	-305.0	364.4
P ₄ O ₆ (s)	-1640.1	—	—
P ₄ O ₁₀ (s)	-2984.0	-2697.0	228.86
PO ₄ ³⁻ (aq)	-1277	-1019	-222
HPO ₃ (s)	-948.5	—	—
HPO ₄ ²⁻ (aq)	-1292.1	-1089.3	-33
H ₂ PO ₄ ²⁻ (aq)	-1296.3	-1130.4	90.4
H ₃ PO ₂ (s)	-604.6	—	—
H ₃ PO ₃ (s)	-964.4	—	—
H ₃ PO ₄ (s)	-1279.0	-1119.1	110.50
H ₃ PO ₄ (l)	-1266.9	-1124.3	110.5
H ₄ P ₂ O ₇ (s)	-2241.0	—	—
POCl ₃ (l)	-597.1	-520.8	222.5
POCl ₃ (g)	-558.5	-512.9	325.5
potassium			
K(s)	0	0	64.7
K(g)	89.0	60.5	160.3
K ⁺ (aq)	-252.4	-283.3	102.5
KF(s)	-576.27	-537.75	66.57
KCl(s)	-436.5	-408.5	82.6
rubidium			
Rb ⁺ (aq)	-246	-282.2	124
silicon			
Si(s)	0	0	18.8
Si(g)	450.0	405.5	168.0

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SiO ₂ (s)	-910.7	-856.3	41.5
SiH ₄ (g)	34.3	56.9	204.6
H ₂ SiO ₃ (s)	-1188.67	-1092.44	133.89
H ₄ SiO ₄ (s)	-1481.14	-1333.02	192.46
SiF ₄ (g)	-1615.0	-1572.8	282.8
SiCl ₄ (l)	-687.0	-619.8	239.7
SiCl ₄ (g)	-662.75	-622.58	330.62
SiC(s, <i>beta cubic</i>)	-73.22	-70.71	16.61
SiC(s, <i>alpha hexagonal</i>)	-71.55	-69.04	16.48
silver			
Ag(s)	0	0	42.55
Ag(g)	284.9	246.0	172.89
Ag ⁺ (aq)	105.6	77.11	72.68
Ag ₂ O(s)	-31.05	-11.20	121.3
AgCl(s)	-127.0	-109.8	96.3
Ag ₂ S(s)	-32.6	-40.7	144.0
sodium			
Na(s)	0	0	51.3
Na(g)	107.5	77.0	153.7
Na ⁺ (aq)	-240.1	-261.9	59
Na ₂ O(s)	-414.2	-375.5	75.1
NaCl(s)	-411.2	-384.1	72.1
strontium			
Sr ²⁺ (aq)	-545.8	-557.3	-32.6
sulfur			
S ₈ (s) (rhombic)	0	0	256.8
S(g)	278.81	238.25	167.82
S ²⁻ (aq)	41.8	83.7	22
SO ₂ (g)	-296.83	-300.1	248.2
SO ₃ (g)	-395.72	-371.06	256.76
SO ₄ ²⁻ (aq)	-909.3	-744.5	20.1

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S ₂ O ₃ ²⁻ (aq)	-648.5	-522.5	67
H ₂ S(g)	-20.6	-33.4	205.8
HS ⁻ (aq)	-17.7	12.6	61.1
H ₂ SO ₄ (l)	-813.989	690.00	156.90
HSO ₄ ²⁻ (aq)	-885.75	-752.87	126.9
H ₂ S ₂ O ₇ (s)	-1273.6	—	—
SF ₄ (g)	-728.43	-684.84	291.12
SF ₆ (g)	-1220.5	-1116.5	291.5
SCl ₂ (l)	-50	—	—
SCl ₂ (g)	-19.7	—	—
S ₂ Cl ₂ (l)	-59.4	—	—
S ₂ Cl ₂ (g)	-19.50	-29.25	319.45
SOCl ₂ (g)	-212.55	-198.32	309.66
SOCl ₂ (l)	-245.6	—	—
SO ₂ Cl ₂ (l)	-394.1	—	—
SO ₂ Cl ₂ (g)	-354.80	-310.45	311.83
tin			
Sn(s)	0	0	51.2
Sn(g)	301.2	266.2	168.5
SnO(s)	-285.8	-256.9	56.5
SnO ₂ (s)	-577.6	-515.8	49.0
SnCl ₄ (l)	-511.3	-440.1	258.6
SnCl ₄ (g)	-471.5	-432.2	365.8
titanium			
Ti(s)	0	0	30.7
Ti(g)	473.0	428.4	180.3
TiO ₂ (s)	-944.0	-888.8	50.6
TiCl ₄ (l)	-804.2	-737.2	252.4
TiCl ₄ (g)	-763.2	-726.3	353.2
tungsten			
W(s)	0	0	32.6

Table G1

Standard Thermodynamic Properties for Selected Substances

Substance	ΔH_f° (kJ mol ⁻¹)	ΔG_f° (kJ mol ⁻¹)	S° (J K ⁻¹ mol ⁻¹)
W(g)	849.4	807.1	174.0
WO ₃ (s)	-842.9	-764.0	75.9
zinc			
Zn(s)	0	0	41.6
Zn(g)	130.73	95.14	160.98
Zn ²⁺ (aq)	-153.9	-147.1	-112.1
ZnO(s)	-350.5	-320.5	43.7
ZnCl ₂ (s)	-415.1	-369.43	111.5
ZnS(s)	-206.0	-201.3	57.7
ZnSO ₄ (s)	-982.8	-871.5	110.5
ZnCO ₃ (s)	-812.78	-731.57	82.42
complexes			
[Co(NH ₃) ₄ (NO ₂) ₂]NO ₃ , <i>cis</i>	-898.7	—	—
[Co(NH ₃) ₄ (NO ₂) ₂]NO ₃ , <i>trans</i>	-896.2	—	—
NH ₄ [Co(NH ₃) ₂ (NO ₂) ₄]	-837.6	—	—
[Co(NH ₃) ₆][Co(NH ₃) ₂ (NO ₂) ₄] ₃	-2733.0	—	—
[Co(NH ₃) ₄ Cl ₂]Cl, <i>cis</i>	-874.9	—	—
[Co(NH ₃) ₄ Cl ₂]Cl, <i>trans</i>	-877.4	—	—
[Co(en) ₂ (NO ₂) ₂]NO ₃ , <i>cis</i>	-689.5	—	—
[Co(en) ₂ Cl ₂]Cl, <i>cis</i>	-681.2	—	—
[Co(en) ₂ Cl ₂]Cl, <i>trans</i>	-677.4	—	—
[Co(en) ₃](ClO ₄) ₃	-762.7	—	—
[Co(en) ₃]Br ₂	-595.8	—	—
[Co(en) ₃]I ₂	-475.3	—	—
[Co(en) ₃]I ₃	-519.2	—	—
[Co(NH ₃) ₆](ClO ₄) ₃	-1034.7	-221.1	615
[Co(NH ₃) ₅ NO ₂](NO ₃) ₂	-1088.7	-412.9	331
[Co(NH ₃) ₆](NO ₃) ₃	-1282.0	-524.5	448
[Co(NH ₃) ₅ Cl]Cl ₂	-1017.1	-582.5	366.1
[Pt(NH ₃) ₄]Cl ₂	-725.5	—	—
[Ni(NH ₃) ₆]Cl ₂	-994.1	—	—

Table G1

Standard Thermodynamic Properties for Selected Substances

Substance	ΔH_f° (kJ mol ⁻¹)	ΔG_f° (kJ mol ⁻¹)	S° (J K ⁻¹ mol ⁻¹)
[Ni(NH ₃) ₆]Br ₂	-923.8	—	—
[Ni(NH ₃) ₆]I ₂	-808.3	—	—

Table G1