B

STANDARD STATE THERMODYNAMIC PROPERTIES OF SELECTED MINERALS AND OTHER COMPOUNDS

Part 1. Inorganic Substances

Data from Wagman et al., The NBS tables of chemical thermodynamic properties. Jour. Physical and Chemical Reference Data, v. 11, Supplement no. 2, 1982; with a few additions from other sources—Al species from Drever (1988); silica species and all volume data from SUPCRT92 (Johnson et al., 1992).

Formula	Form	Mol. wt. g mol^{-1}	$\Delta_f H°$ kJ mol^{-1}	$\Delta_f G°$ kJ mol^{-1}	$S°$ J mol^{-1} K^{-1}	$C_p°$ J mol^{-1} K^{-1}	$V°$ cm^3 mol^{-1}
Aluminum							
Al	s	26.9815	0	0	28.33	24.35	
Al^{3+}	aq	26.9815	−531.	−485.	−321.7	—	−45.3
$Al(OH)^{2+}$	aq		−767.0	−693.7	—	—	
$Al(OH)_2^+$	aq		−1010.7	−901.4	—	—	
$Al(OH)_3^\circ(aq)$	aq		−1250.4	−1100.7	—	—	
$Al(OH)_4^-$	aq	95.0111	−1490.0	−1307.0	102.9	—	45.60
Al_2O_3	α, corundum	101.9612	−1675.7	−1582.3	50.92	79.04	25.575
$Al_2O_3 \cdot H_2O$	boehmite	119.9766	−1980.7	−1831.7	96.86	131.25	39.07
$Al_2O_3 \cdot H_2O$	diaspore	119.9766	−1998.91	−1841.78	70.67	106.19	35.52
$Al_2O_3 \cdot 3H_2O$	gibbsite	156.0074	−2586.67	−2310.21	136.90	183.47	63.912
$Al_2O_3 \cdot 3H_2O$	bayerite	156.0074	−2576.5	—	—	—	
$Al(OH)_3$	amorphous	78.0037	−1276.	—	—	—	
Al_2SiO_5	andalusite	162.0460	−2590.27	−2442.66	93.22	122.72	51.53
Al_2SiO_5	kyanite	162.0460	−2594.29	−2443.88	83.81	121.71	44.09
Al_2SiO_5	sillimanite	162.0460	−2587.76	−2440.99	96.11	124.52	49.90
$Al_2Si_2O_7 \cdot 2H_2O$	kaolinite	258.1616	−4119.6	−3799.7	205.0	246.14	99.52
$Al_2Si_2O_7 \cdot 2H_2O$	halloysite	258.1616	−4101.2	−3780.5	203.3	246.27	99.30
$Al_2Si_2O_7 \cdot 2H_2O$	dickite	258.1616	−4118.3	−3795.9	197.1	239.49	99.30
$Al_6Si_2O_{13}$	mullite	426.0532	−6816.2	−6432.7	255.	326.10	-
$Al_2Si_4O_{10}(OH)_2$	pyrophyllite	360.3158	−5642.04	−5268.14	239.41	294.34	126.6
Barium							
Ba	s	137.3400	0	0	62.8	28.07	
Ba^{2+}	aq	137.3400	−537.64	−560.77	9.6	—	−12.9
BaO	s	153.3394	−553.5	−525.1	70.42	47.78	
BaO_2	s	169.3388	−634.3	—	—	66.9	
BaF_2	s	175.3368	−1207.1	−1156.8	96.36	71.21	
BaS	s	169.4040	−460.	−456.	78.2	49.37	
$BaSO_4$	barite	233.4016	−1473.2	−1362.2	132.2	101.75	52.10
$BaCO_3$	witherite	197.3494	−1216.3	−1137.6	112.1	85.35	45.81
$BaSiO_3$	s	213.4242	−1623.60	−1540.21	109.6	90.00	
Calcium							
Ca	s	40.0800	0	0	41.42	25.31	
Ca^{2+}	aq	40.0800	−542.83	−553.58	−53.1	—	−18.4
CaO	s	56.0794	−635.09	−604.03	39.75	42.80	
$Ca(OH)_2$	portlandite	74.0948	−986.09	−898.49	83.39	87.49	
CaF_2	fluorite	78.0768	−1219.6	−1167.3	68.87	67.03	24.542
CaS	s	72.1440	−482.4	−477.4	56.5	47.40	
$CaSO_4$	anhydrite	136.1416	−1434.11	−1321.79	106.7	99.66	45.94

Formula	Form	Mol. wt. g mol^{-1}	$\Delta_f H°$ kJ mol^{-1}	$\Delta_f G°$ kJ mol^{-1}	$S°$ J mol^{-1} K^{-1}	$C_p°$ J mol^{-1} K^{-1}	$V°$ cm^3 mol^{-1}
$CaSO_4 \cdot 2H_2O$	gypsum	172.1724	−2022.63	−1797.28	194.1	186.02	
$Ca_3(PO_4)_2$	β,whitlockite	310.1828	−4120.8	−3884.7	236.0	227.82	
$Ca_3(PO_4)_2$	α	310.1828	−4109.9	−3875.5	240.91	231.58	
$CaCO_3$	calcite	100.0894	−1206.92	−1128.79	92.9	81.88	36.934
$CaCO_3$	aragonite	100.0894	−1207.13	−1127.75	88.7	81.25	34.150
$CaSiO_3$	wollastonite	116.1642	−1634.94	−1549.66	81.92	85.27	39.93
$CaSiO_3$	pseudowollastonite	116.1642	−1628.4	−1544.7	87.36	86.48	
$CaAl_2SiO_6$	Ca-Al pyroxene	218.1254	−3298.2	−3122.0	141.4	165.7	
$CaAl_2Si_2O_8$	anorthite	278.2102	−4227.9	−4002.3	199.28	211.42	100.79
$CaTiO_3$	perovskite	135.9782	−1660.6	−1575.2	93.64	97.65	
$CaTiSiO_5$	sphene	196.0630	−2603.3	−2461.8	129.20	138.95	
$CaMg(CO_3)_2$	dolomite	184.4108	−2326.3	−2163.4	155.18	157.53	64.365
$CaMgSi_2O_6$	diopside	216.5604	−3206.2	−3032.0	142.93	166.52	66.090
Carbon							
C	graphite	12.0112	0	0	5.740	8.527	5.298
C	diamond	12.0112	1.895	2.900	2.377	6.113	3.417
CO_3^{2-}	aq	60.0094	−677.149	−527.81	−56.9	—	−6.1
HCO_3^-	aq	61.0174	−691.99	−586.77	91.2	—	24.2
CO	g	28.0106	−110.525	−137.168	197.674	29.142	24465.6
CO_2	g	44.0100	−393.509	−394.359	213.74	37.11	24465.6
CO_2	aq	44.0100	−413.80	−385.98	117.6	—	32.8
H_2CO_3	aq	62.0254	−679.339	−623.109	283.65	—	
CH_4	g	16.0432	−74.81	−50.72	186.264	35.309	24465.6
C_2H_6	g	30.0704	−84.68	−32.82	229.60	52.63	24465.6
CN	g	26.0179	437.6	407.5	202.6	29.16	
CN^-	aq	26.0179	150.6	172.4	94.1	—	
HCN	g	27.0259	135.1	124.7	201.78	35.86	
HCN	aq	27.0259	107.1	119.7	124.7	—	
Chlorine							
Cl_2	g	70.9060	0	0	233.066	33.907	24465.6
Cl^-	aq	35.4530	−167.159	−131.228	56.5	−136.4	17.3
HCl	aq	36.4610	−167.159	−131.228	56.5	−136.4	17.3
HCl	g	36.4610	−92.307	−95.299	186.908	29.12	24465.6
Copper							
Cu	s	63.5400	0	0	33.15	24.435	
Cu^+	aq	63.5400	71.67	49.98	40.6	—	
Cu^{2+}	aq	63.5400	64.77	65.49	−99.6	—	
CuO	tenorite	79.5394	−157.3	−129.7	42.63	42.30	
Cu_2O	cuprite	143.0794	−168.6	−146.0	93.14	63.64	
CuS	covellite	96.6040	−53.1	−53.6	66.5	47.82	
Cu_2S	chalcocite	159.1440	−79.5	−86.2	120.9	76.32	

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Fluorine							
F_2	g	37.9968	0	0	202.78	31.30	
HF	g	20.0064	−271.1	−273.2	173.779	29.133	
HF	aq	20.0064	−320.08	−296.82	88.7	—	
F^-		18.9984	−332.63	−278.79	−13.8	−106.7	—
Hydrogen							
H_2	g	2.0160	0	0	130.684	28.824	24465.6
H^+	aq	1.0080	0	0	0	0	0
OH^-	aq	17.0074	−229.994	−157.244	−10.75	−148.5	
H_2O	l	18.0154	−285.830	−237.129	69.91	75.291	18.068
H_2O	g	18.0154	−241.818	−228.572	188.825	33.577	24465.6
Iodine							
I_2	s	253.8088	0	0	116.135	54.438	
I^-	aq	126.9044	−55.19	−51.57	111.3	−142.3	
HI	aq	127.9124	−55.19	−51.57	111.3	—	
IO_3^-	aq	174.9026	−221.3	−128.0	118.4	—	
IO_4^-	aq	190.9020	−155.5	−58.5	222.0	—	
Iron							
Fe	s	55.8470	0	0	27.28	25.10	
Fe^{2+}	aq	55.8470	−89.1	−78.90	−137.7	—	
Fe^{3+}	aq	55.8470	−48.5	−4.7	−315.9	—	
$Fe_{0.947}O$	wüstite	68.8865	−266.27	−245.12	57.49	48.12	
Fe_2O_3	hematite	159.6922	−824.2	−742.2	87.40	103.85	
Fe_3O_4	magnetite	231.5386	−1118.4	−1015.4	146.4	143.43	
FeO(OH)	goethite	88.8538	−559.0	(−487.02)	(60.25)	—	
$Fe(OH)_2$	s	89.8618	−569.0	−486.5	88.	—	
$Fe(OH)_3$	s	106.8692	−823.0	−696.5	106.7	—	
FeS	troilite	87.9110	−100.0	−100.4	60.29	50.54	
FeS_2	pyrite	119.9750	−178.2	−166.9	52.93	62.17	
$FeCO_3$	siderite	115.8564	−740.57	−666.67	92.9	82.13	
Fe_2SiO_4	fayalite	203.7776	−1479.9	−1379.0	145.2	132.88	
Lead							
Pb	s	207.1900	0	0	64.81	26.44	
Pb^{2+}	aq	207.1900	−1.7	−24.43	10.5	—	
PbO	yellow	223.1894	−217.32	−187.89	68.70	45.77	
PbO	red	223.1894	−218.99	−188.93	66.5	45.81	

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PbF_2	s	245.1868	−664.0	−617.1	110.5	—	
$PbCl_2$	s	278.0960	−359.41	−314.10	136.0	—	
PbS	galena	239.2540	−100.42	−98.7	91.2	49.50	
$PbSO_4$	anglesite	303.2516	−919.94	−813.14	148.57	103.207	
$PbCO_3$	cerussite	267.1994	−699.1	−625.5	131.0	87.40	
$PbSiO_3$	s	283.2742	−1145.70	−1062.10	109.6	90.04	
Magnesium							
Mg	s	24.3120	0	0	32.68	24.89	
Mg^{2+}	aq	24.3120	−466.85	−454.8	−138.1	—	
MgO	periclase	40.3114	−601.70	−569.43	26.94	37.15	
$Mg(OH)_2$	brucite	58.3268	−924.54	−833.51	63.18	77.03	
MgF_2	sellaite	62.3088	−1123.4	−1070.2	57.24	61.59	
MgS	s	56.3760	−346.0	−341.8	50.33	45.56	
$MgCO_3$	magnesite	84.3214	−1095.8	−1012.1	65.7	75.52	28.018
$MgCO_3 \cdot 3H_2O$	nesquehonite	138.3676	—	−1726.1	—	—	
$MgSiO_3$	enstatite	100.3962	−1549.00	−1462.09	67.74	81.38	
Mg_2SiO_4	forsterite	140.7076	−2174.0	−2055.1	95.14	118.49	
Manganese							
Mn	s	54.9380	0	0	32.01	26.32	
Mn^{2+}	aq	54.9380	−220.75	−228.1	−73.6	50.	
MnO_4^-	aq	118.9356	−541.4	−447.2	191.2	-82.0	
MnO	manganosite	70.9374	−385.22	−362.90	59.71	45.44	
Mn_3O_4	hausmannite	228.8116	−1387.8	−1283.2	155.6	139.66	
Mn_2O_3	s	157.8742	−959.0	−881.1	110.5	107.65	
MnO_2	pyrolusite	86.9368	−520.03	−465.14	53.05	54.14	
$Mn(OH)_2$	amorphous	88.9528	−695.4	−615.0	99.2	—	
MnS	alabandite	87.0020	−214.2	−218.4	78.2	49.96	
$MnCO_3$	rhodochrosite	114.9474	−894.1	−816.7	85.8	81.50	
$MnSiO_3$	rhodonite	131.0222	−1320.9	−1240.5	89.1	86.44	
Mn_2SiO_4	tephroite	201.9596	−1730.5	−1632.1	163.2	129.87	
Mercury							
Hg	l	200.5900	0	0	76.02	27.983	
Hg	g	200.5900	61.317	31.820	174.96	20.786	
Hg^{2+}	aq	200.5900	171.1	164.4	−32.2	—	
Hg_2^{2+}	aq	401.1800	172.4	153.52	84.5	—	
HgS_2^{2-}	aq	264.7180	—	41.9	—	—	
$HgCl_4^{2-}$	aq	342.4020	−554.0	−446.8	293.	—	
Hg_2Cl_2	s	472.0860	−265.22	−210.745	192.5	—	
HgO	s, red	216.5894	−90.83	−58.539	70.29	44.06	
HgO	s, yellow	216.5894	−90.46	−58.409	71.1	—	
HgS	cinnabar	232.6540	−58.2	−50.6	82.4	48.41	
HgS	metacinnabar	232.6540	−53.6	−47.7	88.3	—	

Formula	Form	Mol. wt. g mol^{-1}	$\Delta_f H°$ kJ mol^{-1}	$\Delta_f G°$ kJ mol^{-1}	$S°$ J mol^{-1} K^{-1}	$C_p°$ J mol^{-1} K^{-1}	$V°$ cm^3 mol^{-1}
Molybdenum							
Mo	s	95.9400	0	0	28.66	24.06	
MoO_3	s	127.9388	−745.09	−667.97	77.74	74.98	
MoS_2	molybdenite	160.0680	−235.1	−225.9	62.59	63.55	
Nickel							
Ni	s	58.7100	0	0	29.87	26.07	
Ni^{2+}	aq	58.7100	−54.0	−45.6	−128.9	—	
NiO	bunsenite	74.7094	−239.7	−211.7	37.99	44.31	
NiS	s	90.7740	−82.0	−79.5	52.97	47.11	
Nitrogen							
N_2	g	28.0134	0	0	191.61	29.125	
NO	g	30.0061	90.25	86.55	210.761	29.844	
NO_2	g	46.0055	33.18	51.31	240.06	37.20	
N_2O	g	44.0128	82.05	104.2	219.85	38.45	
N_2O_4	l	92.0110	−19.50	97.54	209.2	142.7	
N_2O_4	g	92.0110	9.16	97.89	304.29	77.28	
N_2O_5	s	108.0104	−43.1	113.9	178.2	143.1	
N_2O_5	g	108.0104	11.3	115.1	355.7	84.5	
NH_3	g	17.0307	−46.11	−16.45	192.45	35.06	
NO_3^-	aq	62.0049	−205.0	−108.74	146.45	−86.6	
NH_4^+	aq	18.0837	−132.51	−79.31	113.4	79.9	
NH_4OH	aq	35.0461	−366.12	−263.63	181.21	—	
Oxygen							
O_2	g	31.9988	0	0	205.138	29.355	
O_2	aq	31.9988	−11.7	16.4	110.9	—	
OH^-	aq	17.0074	−229.994	−157.244	−10.75	−148.5	
H_2O	l	18.0154	−285.830	−237.129	69.91	75.291	18.068
H_2O	g	18.0154	−241.818	−228.572	188.825	33.577	24465.6
Potassium							
K	s	39.1020	0	0	64.18	29.58	
K^+	aq	39.1020	−252.38	−283.27	102.5	21.8	9.0
KCl	sylvite	74.5550	−436.747	−409.14	82.59	51.30	
$KAlSi_3O_8$	sanidine	278.3367	−3959.7	−3739.9	232.88	204.51	
$KAlSi_3O_8$	microcline	278.3367	−3968.1	−3742.9	214.22	202.38	108.741
$KAlSiO_4$	kaliophilite	158.1671	−2121.3	−2005.3	133.1	119.79	
$KAlSi_2O_6$	leucite	218.2519	−3034.2	−2871.4	200.08	164.14	
$KAl_3Si_3O_{10}OH_2$	muscovite	398.3133	−5984.4	−5608.4	306.3	—	14.087

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Silicon							
Si	s	28.0860	0	0	18.83	20.00	
SiO_2	α-quartz	60.0848	−910.94	−856.64	41.84	44.43	22.688
SiO_2	α-cristobalite	60.0848	−909.48	−855.43	42.68	44.18	
SiO_2	α-tridymite	60.0848	−909.06	−855.26	43.5	44.60	25.740
SiO_2	coesite	60.0848	−906.31	−851.62	40.376	43.51	20.641
SiO_2	amorphous	60.0848	−903.49	−850.70	46.9	44.4	
SiO_2	aq	60.0848	−877.699	−833.411	75.312	318.40	16.1
H_4SiO_4	aq		−1449.359	−1307.669	215.132	468.98	
$HSiO_3^-$	aq		−1125.583	−1013.783	41.84	−137.24	9.5
Silver							
Ag	s	107.8700	0	0	42.55	25.351	
Ag^+	aq	107.8700	105.579	77.107	72.68	21.8	
Ag_2O	s	231.7394	−31.05	−11.20	121.3	65.86	
AgCl	cerargyrite	143.3230	−127.068	−109.789	96.2	50.79	
Ag_2S	acanthite	247.8040	−32.59	−40.67	144.01	76.53	
Ag_2S	argentite	247.8040	−29.41	−39.46	150.6	—	
Sodium							
Na	s	22.9898	0	0	51.21	28.24	
Na^+	aq	22.9898	−240.12	−261.905	59.0	46.4	−1.2
NaCl	halite	58.4428	−411.153	−384.138	72.13	50.50	27.015
Na_2SiO_3	s	122.0638	−1554.90	−1462.80	113.85	—	
$NaAlSiO_4$	nepheline	142.0549	−2092.8	−1978.1	124.3	—	54.16
$NaAlSi_3O_8$	low albite	262.2245	−3935.1	−3711.5	207.40	205.10	100.07
$NaAlSi_2O_6$	jadeite	202.1397	−3030.9	−2852.1	133.5	—	60.40
Sulfur							
S	orthorhombic	32.0640	0	0	31.80	22.64	
S^{2-}	aq	32.0640	33.1	85.8	−14.6	—	
HS^-	aq	33.0720	−17.6	12.08	62.8	—	
SO_4^{2-}	aq	96.0616	−909.27	−744.53	20.1	−293.	
HSO_4^-	aq			−756.0		—	
S_2	g	64.1280	128.37	79.30	228.18	32.47	
H_2S	g	34.0800	−20.63	−33.56	205.79	34.23	
H_2S	aq	34.0800	−39.7	−27.83	121.	—	
SO_2	g	64.0628	−296.830	−300.194	248.22	39.87	
SO_3	g	80.0622	−395.72	−371.06	256.76	50.67	

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Titanium							
Ti	s	47.9000	0	0	30.63	25.02	
TiO	s	63.8994	−519.7	−495.0	50.0	39.96	
TiO_2	anatase	79.8988	−939.7	−884.5	49.92	55.48	
TiO_2	brookite	79.8988	−941.8	—	—	—	
TiO_2	rutile	79.8988	−944.7	−889.5	50.33	55.02	
Uranium							
U	s	238.0290	0	0	50.21	27.665	
UO_2	uraninite	270.0278	−1084.9	−1031.7	77.03	63.60	
UO_3	orthorhombic	286.0272	−1223.8	−1145.9	96.11	81.67	
U^{3+}	aq	238.0290	−489.1	−475.4	192.	—	
U^{4+}	aq	238.0290	−591.2	−531.0	410.	—	
UO_2^{2+}	aq	270.0278	−1019.6	−953.5	−97.5	—	
Zinc							
Zn	s	65.3700	0	0	41.63	25.40	
Zn^{2+}	aq	65.3700	−155.89	−147.06	−112.1	46.	
ZnO	zincite	81.3694	−348.28	−318.30	43.64	40.25	
ZnS	wurtzite	97.4340	−192.63	—	—	—	
ZnS	sphalerite	97.4340	−205.98	−201.29	57.7	46.0	
$ZnCO_3$	smithsonite	125.3794	−812.78	−731.52	82.4	79.71	
Zn_2SiO_4	willemite	222.8236	−1636.74	−1523.16	131.4	123.34	