Appendix A

ENTHALPIES OF FORMATION AT 25°C[1]

Most values refer to the formation of the various compounds from the stable modification of the elements, all at 25°C (273°K) and one atmosphere pressure. Where elements or compounds occur in different modifications, with different enthalpies, this is indicated in the tables. For the states of aggregation the following symbols are used: (s) = solid, (l) = liquid, (g) = gas. Special modifications are shown by name or accepted symbols. For the silicates and a few other substances the values refer to formation from the component oxides. This is indicated in the tables.

The enthalpy of formation at higher temperatures may be calculated from the equation:

$$\Delta H_T^\circ = \Delta H_{298}^\circ + \Delta(H_T^\circ - H_{298}^\circ)$$

Here $\Delta(H_T^\circ - H_{298}^\circ)$ is the difference between the enthalpy increments, above 25°C, for the product and for the elements. These data are given in Appendix B.

The enthalpy of formation is, in principle, also a function of pressure. For practically all substances this dependency is very small, however, and the listed values may, without loss in accuracy be used between zero and a few atmospheres, i.e., under all conditions normally encountered in metallurgical processes.

[1] This and the subsequent appendices are available as a separate booklet ("Thermochemical Data for Metallurgists" by the present author) from the *Tapir Publ. Co.*, Trondheim, Norway.

With few exceptions the values given in this part are drawn from: O. Kubaschewski *et al.*: "Metallurgical Thermochemistry," Pergamon Press, London 1967, and the reader is referred to that text for additional data.

Please note that the tables list $-\Delta H^\circ_{298}$, i.e., the enthalpy of formation with opposite sign.

Substance	Mole weight	$-\Delta H^\circ_{298}$ kcal/ mole	Accuracy ±kcal	
Ag(s)	107.9	0		
AgCl(s)	143.3	30.3	0.2	
Ag_2O(s)	231.7	7.3	0.1	
Ag_2S(s)	247.8	7.6	0.2	
Al(s)	27.0	0		
AlF(g)	46.0	61.0	2.0	
AlF_3(s)	84.0	356.0	1.0	
AlCl(g)	62.4	11.6	0.8	
$AlCl_3$(s)	133.3	168.6	0.5	
Al_2O_3(s)	102.0	400.0	1.5	
AlN(s)	41.0	76.5	1.0	
Al_4C_3(s)	144.0	51.5	2.0	
Andalusite	162.1	1.3†	0.5	†Al_2SiO_5
Kyanite	162.1	1.9†	0.5	from oxides.
Sillimanite	162.1	0.6†	0.5	
Mullite	426.0	−7.0‡	0.5	‡$Al_6Si_2O_{13}$ from oxides.
As(s)	74.9	0		
As_2O_3(s)	197.8	156.6	1.0	
As_2O_4(s)	229.8	218.5	1.5	
As_2S_3(s)	246.0	30.0	3.0	
As_2S_5(s)	310.1	35.0	3.0	
B(s)	10.8	0		
BN(s)	24.8	60.5	0.8	
Ba(s)	137.3	0		
$BaCl_2$(s)	208.2	205.4	0.6	
BaO(s)	153.3	139.0	2.0	
BaO_2(s)	169.3	152.5	3.0	
$BaSO_4$(s)	233.4	350.2	5.0	
$BaCO_3$(s)	197.3	290.0	7.5	
C(graphite)	12.0	0		
C(diamond)	12.0	−0.454	0.03	
C(coke etc.)	12.0	−3.0	1.5	
CH_4(g)	16.0	17.89	0.1	
CCl_4(l)	153.8	33.3	0.5	
CCl_4(g)	153.8	25.5	0.4	
$COCl_2$(g)	98.9	53.3	1.5	
CO(g)	28.0	26.40	0.03	
CO_2(g)	44.0	94.05	0.01	
CS_2(l)	76.1	−21.0	1.0	
CS_2(g)	76.1	−27.7	1.0	
COS(g)	60.1	33.9	1.0	
Ca(s)	40.1	0		
CaF_2(s)	78.1	292.0	3.5	
$CaCl_2$(s)	111.0	191.4	1.0	
CaO(s)	56.1	151.6	0.4	
CaS(s)	72.1	110.0	2.5	
$CaSO_4$(s)	136.1	342.4	3.5	
Ca_3P_2(s)	182.2	120.0	6.0	
CaC_2(s)	64.1	14.1	2.0	
$CaCO_3$(s)	100.1	288.4	0.7	
CaSi(s)	68.2	36.0	2.0	
$CaSi_2$(s)	96.3	36.0	3.0	
Ca_2Si(s)	108.3	50.0	3.0	
$CaSiO_3$(s)	116.2	21.5*	0.3	
Ca_2SiO_4(s)	172.3	30.2*	1.5	*From
Ca_3SiO_5(s)	228.3	27.0*	1.5	oxides
$CaAl_2$(s)	94.0	54.0	3.0	
$CaAl_2O_4$(s)	158.0	3.7*	0.4	*From
$Ca_3Al_2O_6$(s)	270.2	1.6*	0.4	oxides.
Cd(s)	112.4	0		
$CdCl_2$(s)	183.3	93.0	0.5	
CdO(s)	128.4	61.1	0.7	
CdS(s)	144.5	34.5	0.5	
$CdSO_4$(s)	208.5	221.4	1.0	
Ce(s)	140.1	0		
CeO_2(s)	172.1	260.2	2.5	
Co(s)	58.9	0		
$CoCl_2$(s)	129.8	77.8	4.0	
CoO(s)	74.9	57.1	0.5	
CoS(s)	91.0	21.1	1.0	
Co_3S_4(s)	305.0	75.0	3.0	
CoS_2(s)	123.1	33.5	4.0	
$CoSO_4$(s)	155.0	207.5	6.0	
Cr(s)	52.0	0		
$CrCl_2$(s)	122.9	97.0	3.5	
$CrCl_3$(s)	158.4	132.0	5.0	
Cr_2O_3(s)	152.0	270.0	2.5	
CrO_3(s)	100.0	138.5	2.5	
Cr_4C(s)	220.0	16.4	1.5	
Cr_7C_3(s)	400.0	42.5	2.5	
Cr_3C_2(s)	180.0	21.0	2.0	
Cu(s)	63.5	0		
CuCl(s)	99.0	32.2	0.7	
$CuCl_2$(s)	134.4	49.2	2.5	
Cu_2O(s)	143.1	40.0	0.7	
CuO(s)	79.5	37.1	0.8	
Cu_2S(s)	159.1	19.6	0.4	
CuS(s)	95.6	12.1	0.5	
$CuSO_4$(s)	159.6	184.0	2.5	
Fe	55.8	0		
$FeCl_2$(s)	126.8	81.8	0.2	
$FeCl_3$(s)	162.2	95.7	0.2	
FeO(s)	71.9	63.2§	0.3	§$Fe_{0.95}O$
Fe_3O_4(s)	231.6	266.9	1.0	

Substance	Mole weight	$-\Delta H^\circ_{298}$ kcal/ mole	Accuracy ±kcal	
$Fe_2O_3(s)$	159.7	196.3	0.8	
FeS(s)	87.9	22.8	0.3	
$FeS_2(s)$	120.0	42.4	1.5	
$FeSO_4(s)$	151.9	220.5	6.0	
$Fe_4N(s)$	237.4	2.6	2.0	
$Fe_2N(s)$	125.7	0.9	2.0	
$Fe_3P(s)$	198.5	39.0	2.0	
$Fe_3C(s)$	179.6	−5.4	1.5	
$FeCO_3(s)$	115.9	178.7	3.0	
FeSi(s)	83.9	19.2	1.5	
$Fe_2SiO_4(s)$	203.8	2.6‖	2.5	‖From 0.1 Fe + 2 $Fe_{0.95}O$ + SiO_2.
$FeCr_2O_4(s)$	223.9	1.3*	2.5	
$H_2(g)$	2.016	0		*From oxides.
HF(g)	20.0	64.8	0.5	
HCl(g)	36.5	22.0	0.1	
$H_2O(g)$	18.0	57.80	0.01	
$H_2O(l)$	18.0	68.32	0.01	
$H_2S(g)$	34.1	4.9	0.1	
Hg(l)	200.6	0		
HgCl(s)	236.0	31.5	0.3	
$HgCl_2(s)$	271.5	55.0	1.5	
HgO(s, red)	216.6	21.7	0.2	
HgS(s, red)	232.7	13.9	1.5	
K(s)	39.1	0		
KF(s)	58.1	134.5	1.0	
KCl(s)	74.6	104.2	0.2	
$K_2O(s)$	94.2	86.4	2.0	
KOH(s)	56.1	101.8	0.5	
$K_2SO_4(s)$	174.3	342.6	1.0	
$K_2CO_3(s)$	138.2	188.55	1.5	
$K_2SiO_3(s)$	154.3	62.5*	7.0	*From oxides.
Mg(s)	24.3	0		
$MgCl_2(s)$	95.2	153.4	0.2	
MgO(s)	40.3	143.7	0.2	
MgS(s)	56.4	83.0	2.0	
$MgSO_4(s)$	120.4	305.5	5.0	
$Mg_2C_3(s)$	84.7	−19.0	8.0	
$MgC_2(s)$	48.3	−21.0	5.0	
$MgCO_3(s)$	84.3	262.0	3.0	
$Mg_2Si(s)$	76.7	19.0	1.0	
$Mg_2SiO_4(s)$	140.7	15.1*	1.0	*From oxides.
$MgSiO_3(s)$	100.4	8.7*	0.7	
Mn(s)	54.9	0		
$MnCl_2(s)$	125.8	115.2	0.5	
MnO(s)	70.9	92.0	0.5	
$Mn_3O_4(s)$	228.8	331.4	1.0	
$Mn_2O_3(s)$	157.9	228.7	1.2	
$MnO_2(s)$	86.9	124.3	0.5	
$Mn_2O_7(s)$	221.9	174.1	2.5	
MnS(s)	87.0	49.0	0.5	
$MnS_2(s)$	119.1	49.5	2.5	
$MnSO_4(s)$	151.0	254.2	1.0	
$Mn_3C(s)$	176.8	3.6	3.0	
$MnCO_3(s)$	115.0	213.9	1.2	
$MnSiO_3(s)$	131.0	5.9*	0.4	*From oxides.
$Mn_2SiO_4(s)$	202.0	11.8*	0.7	
Mo(s)	95.9	0		
$MoO_2(s)$	127.9	140.0	0.9	
$MoO_3(s)$	143.9	178.2	0.5	
$Mo_2S_3(s)$	288.1	92.5	4.0	
$MoS_2(s)$	160.1	60.4	3.0	
$Mo_2N(s)$	205.9	16.6	0.5	
$Mo_2C(s)$	203.9	−4.2	5.0	
$N_2(g)$	28.0	0		
$NH_3(g)$	17.0	11.0	0.2	
$N_2O(g)$	44.0	−19.6	0.4	
NO(g)	30.0	−21.6	0.4	
$NO_2(g)$	46.0	−8.0	0.2	
Na(s)	23.0	0		
NaF(s)	42.0	137.3	1.0	
NaCl(s)	58.5	98.6	0.2	
$Na_2O(s)$	62.0	100.7	1.2	
NaOH(s)	40.0	102.3	1.2	
$Na_2S(s)$	78.1	92.4	2.0	
$Na_2SO_4(s)$	142.1	333.5	2.0	
$Na_2CO_3(s)$	106.0	271.6	2.5	
$Na_2SiO_3(s)$	122.1	55.5*	3.5	*From oxides.
$Na_2Si_2O_5(s, \alpha)$	182.2	60.5*	3.5	
Nb(s)	92.9	0		
NbO(s)	108.9	98.5	2.0	
$NbO_2(s)$	124.9	190.4	1.5	
$Nb_2O_5(s)$	265.8	455.0	2.0	
NbC(s)	104.9	33.7	1.5	
Ni(s)	58.7	0		
NiCl(g)	129.6	−55.0	9.0	
$NiCl_2(s)$	129.6	73.0	0.5	
NiO(s)	74.7	57.5	0.5	
$Ni_3S_2(s)$	240.3	47.5	2.5	
NiS(s)	90.8	22.2	1.4	
$NiS_2(s)$	122.8	34.0	4.0	
$NiSO_4(s)$	154.8	212.5	5.0	
$Ni_3C(s)$	188.1	−9.0	1.5	
$NiCO_3(s)$	118.7	162.7	3.0	
$Ni(CO)_4(g)$	170.8	36.4¶	1.0	¶From Ni + 4CO.
P(s, white)	31.0	0		
P(s, red)	31.0	4.4	0.4	
$PCl_3(g)$	137.3	66.4	1.0	
$PCl_3(l)$	137.3	74.3	0.8	
$PCl_5(g)$	208.2	87.3	3.0	
$PCl_5(s)$	208.2	106.0	3.0	
$P_2O_5(s)$	141.9	356.6	2.5	
Pb(s)	207.2	0		
$PbCl_2(s)$	278.1	85.8	0.5	
PbO(s, red)	223.2	52.4	0.2	
$Pb_3O_4(s)$	685.6	175.6	4.0	
$PbO_2(s)$	239.2	66.1	1.0	
PbS(s)	239.3	22.5	0.5	
$PbSO_4(s)$	303.3	219.5	0.8	
$PbCO_3(s)$	267.2	167.3	2.5	
$Pb_2SiO_4(s)$	506.5	7.0*	3.5	*From oxides.
$PbSiO_3(s)$	283.3	2.5*	2.0	

Substance	Mole weight	$-\Delta H^\circ_{298}$ kcal/ mole	Accuracy ±kcal	
S(s,rh.)	32.1	0		
S(s,monocl.)	32.1	−0.07	0.01	
S(g)	32.1	−56.8	1.5	
S_2(g)	64.1	−31.0	1.0	
SCl_4(l)	173.9	13.6	3.0	
SO_2(g)	64.1	70.95	0.1	
SO_3(g)	80.1	94.4	0.3	
Sb(s)	121.8	0		
$SbCl_3$(s)	228.1	91.4	0.5	
$SbCl_5$(l)	299.0	104.8	3.0	
Sb_2O_3(s)	291.5	169.4	1.0	
Sb_2S_3(s, black)	339.7	40.5	5.0	
$Sb_2(SO_4)_3$(s)	531.7	575.3	8.0	
Si(s)	28.1	0		
SiF_4(g)	104.1	385.0	3.0	
$SiCl_4$(l)	169.9	164.0	1.5	
SiO(g)	44.1	23.2	2.5	
SiO_2(s)**	60.1	217.0	1.0	**α-quartz.
SiO_2(s)††	60.1	216.1	1.0	††β-cristobalite.
SiS_2(s)	92.2	49.0	6.0	
SiS(g)	60.2	−28.0	10.0	
SiC(s)	40.1	15.0	1.0	
Sn(s, white)	118.7	0		
Sn(s, gray)	118.7	0.50	0.05	
$SnCl_2$(s)	189.6	83.6	1.5	
$SnCl_4$(l)	260.5	130.3	1.5	
SnO_2(s)	150.7	138.7	0.2	
SnS(s)	150.8	25.1	1.2	
SnS_2(s)	182.8	40.0	4.0	
Ti(s)	47.9	0		
$TiCl_2$(s)	118.8	122.8	3.0	
$TiCl_4$(g)	189.7	181.7	0.8	
$TiCl_4$(l)	189.7	191.6	0.6	
TiO(s)	63.9	123.9	0.8	
Ti_2O_3(s)	143.8	362.9	0.8	
Ti_3O_5(s)	223.7	586.9	1.5	
TiO_2(s)	79.9	225.5	1.0	
TiC(s)	59.9	43.9	1.5	
V(s)	50.9	0		
V_2O_3(s)	149.9	293.0	7.0	
V_2O_5(s)	181.9	372.3	4.5	
Zn(s)	65.4	0		
$ZnCl_2$(s)	136.3	99.5	0.3	
ZnO(s)	81.4	83.2	0.3	
ZnS(s)	97.4	48.2	2.0	
$ZnSO_4$(s)	161.4	233.9	2.0	
$ZnCO_3$(s)	125.4	194.2	0.3	
Zn_2SiO_4(s)	222.8	7.0*	1.5	*From oxides.
Zr(s)	91.2	0		
ZrO_2(s)	123.2	259.5	1.5	
ZrN(s)	105.2	87.3	0.5	
ZrC(s)	103.2	44.1	1.6	