ENTHALPY OF FORMATION

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Standard enthalpy of formation ($\Delta H_f°$): Also called the standard heat of formation of a substance

Standard heat of formation: The amount of heat absorbed or released when one mole of the substance is formed at 25°C and 100kPa (SATP) from its elements in their standard states

$\Delta H_f°$ units are always in kJ/mol

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Standard heat of formation: The amount of heat absorbed or released when one mole of the substance is formed at 25°C and 100kPa (SATP) from its **elements** <u>in their standard states</u>

Example: What equation represents the formation of nitric acid?

Nitric acid = $HNO_{3(l)}$

Elements: hydrogen nitrogen oxygen

What are these elements in their standard (most common) states?

$$\frac{1}{2} H_{2(g)} + \frac{1}{2} N_{2(g)} + 3/2\ O_{2(g)} \rightarrow HNO_{3(l)}$$

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The $\Delta H_f°$ for elements in their standard states are zero

Compound	$\Delta G_f°$ /kJ mol^{-1}	Compound	$\Delta G_f°$ /kJ mol^{-1}
$AgCl(s)$	−109.7	$H_2O(g)$	−228.6
$AgN_3(s)$	378.5	$H_2O(l)$	−237.2
$Ag_2O(s)$	−10.8	$H_2O_2(l)$	−114.0
$Al_2O_3(s)$	−1576.4	$H_2S(g)$	−33.0
$Br_2(l)$	0.0	$HgO(s)$	−58.5
$Br_2(g)$	3.1	$I_2(s)$	0.0
$CaO(s)$	−604.2	$I_2(g)$	19.4
$CaCO_3(s)$	−1128.8	$KCl(s)$	−408.3
C—graphite	0.0	$KBr(s)$	−393.1
C—diamond	2.9	$MgO(s)$	−569.6
$CH_4(g)$	−50.8	$MgH_2(s)$	76.1
$C_2H_2(g)$	209.2	$NH_3(g)$	16.7
$C_2H_4(g)$	68.2	$NO(g)$	86.7
$C_2H_6(g)$	−32.9	$NO_2(g)$	51.8
$C_6H_6(l)$	124.5	$N_2O_4(g)$	98.3
$CO(g)$	−137.3	$NF_3(g)$	−124.7
$CO_2(g)$	−394.4	$NaCl(s)$	−384.0
$CuO(s)$	−127.2	$NaBr(s)$	−347.6
$Fe_2O_3(s)$	−741.0	$O_3(g)$	163.4
$HBr(g)$	−53.2	$SO_2(g)$	−300.4
$HCl(g)$	−95.3	$SO_3(g)$	−370.4
$HI(g)$	1.3	$ZnO(s)$	−318.2

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Determine the equations for the formation of:

a) $KBrO_3$

b) C_2H_5OH

c) $NaHCO_3$

Don't forget that the equation must result in the formation of **one** mole of the desired compound.

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Now we can assign the $\Delta H°_f$ of the product as the $\Delta H°$ of the whole reaction

$2C_{(s)} + 3H_{2(g)} + 1/2O_{2(g)} \rightarrow C_2H_5OH_{(l)}$ $\Delta H° = -235.2 kJ/mol$

This additional equation may assist solving Hess' Law questions.

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How are these equations and $\Delta H°_f$ values useful?

$$CaO_{(s)} + H_2O_{(l)} \rightarrow Ca(OH)_{2(s)}$$

By knowing the $\Delta H°_f$ of each of the chemicals in the above reaction, you can calculate the $\Delta H°$ of the reaction without using thermochemical equations and Hess' Law

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$\Delta H°_f$

Formation reactions and their $\Delta H°_f$ values may be manipulated to determine balanced equation and the $\Delta H°$ value of chemical reactions.

Don't forget that the equations should be multiplied by the appropriate factor, as necessary.

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Using $\Delta H°_f$ values, calculate the $\Delta H°$ of combustion of one mole of ethanol to produce carbon dioxide gas and liquid water.

$$C_2H_5OH_{(l)} + 3\ O_{2(g)} \rightarrow 2\ CO_{2(g)} + 3\ H_2O_{(l)}$$

-235.2kJ/mol 0.0000kJ/mol -393.5kJ/mol -285.8kJ/mol

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Using $\Delta H°_f$ values, calculate the $\Delta H°$ for the following reaction:

$$NaOH_{(s)} \quad + \quad HCl_{(g)} \rightarrow \quad NaCl_{(s)} \quad + \quad H_2O_{(l)}$$

-425.6kJ/mol -92.30kJ/mol -411.2kJ/mol -285.8kJ/mol

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Enthalpy of Combustion:

What is the reaction to produce $C_6H_{12}O_6$?

$6\ CO_2 + 6\ H_2O \rightarrow 6\ O_2 + C_6H_{12}O_6$

Where does this naturally occur?

How do we measure it?

In plant chloroplasts; it is not easy to measure.

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Enthalpy of Combustion:

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O$$

For complex organics, such as $C_6H_{12}O_6$, it is difficult to directly measure its formation. Instead, the compound is combusted and the products analyzed to determine $\Delta H°_f$ for the original compound.

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Enthalpy of Combustion:

$$\Delta H^\circ_c$$

standard heat of combustion - the ΔH° for the combustion of one mole of compound

Ex. $CH_3OH_{(g)} + O_{2(g)} \rightarrow CO_{2(g)} + H_2O_{(l)}$

$\Delta H^\circ_c = -727 kJ$

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Enthalpy of Combustion:

$C_2H_{4(g)} + 3\ O_{2(g)} \rightarrow 2\ CO_{2(g)} + 2\ H_2O_{(l)} \quad \Delta H°_c = -1386\ kJ$

Calculate the $\Delta H°_f$ for C_2H_4.

~~$2\ CO_{2(g)} + 2\ H_2O_{(l)} \rightarrow C_2H_{4(g)} + 3\ O_{2(g)} \quad \Delta H° = +1386\ kJ$~~

Can't simply reverse this equation.

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Calculate the ΔH°_f for C_2H_4.

$C_2H_{4(g)} + 3\ O_{2(g)} \rightarrow 2\ CO_{2(g)} + 2\ H_2O_{(l)} \quad \Delta H^\circ_c = -1386\ kJ$

x 0.000kJ -393.5kJ -285.8kJ

ENTHALPY OF FORMATION

Enthalpy of Combustion:

$$C_2H_{4(g)} + 3\ O_{2(g)} \rightarrow 2\ CO_{2(g)} + 2\ H_2O_{(l)} \qquad \Delta H°_c = -1386\ kJ$$

Calculate the $\Delta H°_f$ for C_2H_4.

$$2C_{(s)} + 2H_{2(g)} \rightarrow C_2H_{4(g)} \quad \Delta H_f° = ?$$

① $2\ CO_{2(g)} + 2\ H_2O_{(l)} \rightarrow C_2H_{4(g)} + 3\ O_{2(g)} \qquad \Delta H° = +1386\ kJ$

② $C_{(s)} + O_{2(g)} \rightarrow CO_{2(g)} \qquad \Delta H° = -393.5\ kJ$

③ $H_{2(g)} + 1/2O_{2(g)} \rightarrow H_2O_{(l)} \qquad \Delta H° = -285.8\ kJ$

Table A-6

Thermodynamic Properties (at standard states)

ΔH_f° in kJ/mol ΔG_f° in kJ/mol S° in J/mol·K

concentration of aqueous solutions is 1*M*

Substance	ΔH_f°	ΔG_f°	S°	Substance	ΔH_f°	ΔG_f°	S°
Ag	0	0	42.7	H_3PO_3	−972	—	—
$AgCl$	−127	−110	96.1	H_3PO_4	−1280	−1120	110
$AgCN$	−146	−164	83.7	H_2S	−20.1	−33.0	206
Al	0	0	28.3	$H_2SO_3(aq)$	−614	−538	232
Al_2O_3	−1670	−1580	51.0	$H_2SO_4(aq)$	−908	−742	17.2
$BaCl_2(aq)$	−873	−823	121	$HgCl_2$	−230	−177	—
$BaSO_4$	−1470	−1350	132	Hg_2Cl_2	−265	−211	196
Be	0	0	9.54	Hg_2SO_4	−742	−624	201
Be_3N_2	−568	−512	—	I_2	0	0	117
Bi	0	0	56.9	K	0	0	63.6
$BiCl_3$	−379	−319	190	KBr	−392	−379	96.4
Bi_2S_3	−183	−164	146	$KMnO_4$	−813	−714	172
Br_2	0	0	152	KOH	−426	—	—
CH_4	−74.8	−50.8	186	$LiBr$	−350	—	—
C_2H_4	+52.3	+68.1	219	$LiOH$	−487	−444	50.2
C_2H_6	−84.7	−32.9	229	Mn	0	0	32.0
C_4H_{10}	−125	−15.7	310	$MnCl_2(aq)$	−555	−491	38.9
CO	−111	−137	198	$Mn(NO_3)_2(aq)$	−636	−451	218
CO_2	−393.5	−394.4	214	MnO_2	−521	−466	53.1
CS_2	+87.9	+63.6	151	MnS	−214	—	—
Ca	0	0	41.6	N_2	0	0	192
$Ca(OH)_2$	−987	−897	—	NH_3	−46.2	−16.6	193
Cl_2	0	0	223	NH_4Br	−270	−175	113
$CoCO_3$	−723	−650	—	NO	+90.4	—	211
CoO	−239	−213	43.9	NO_2	+33.8	+51.8	240
Cr_2O_3	−1130	−1050	81.2	Na	0	0	51.0
$CsCl(aq)$	−415	−371	188	$NaBr$	−360	—	—
$Cs_2SO_4(aq)$	−1400	−1310	283	$NaCl$	−411	−384	72.4
CuI	−67.8	−69.5	96.7	$NaNO_3(aq)$	−447	—	—
CuS	−53.1	−53.7	66.5	$NaOH$	−427	—	—
Cu_2S	−79.5	−86.2	121	$Na_2S(aq)$	−437	—	—
$CuSO_4$	−770	−662	113	Na_2SO_4	−1380	−1270	149