Name__________________________ **Honors Chemistry** ___/___/___

Hess's Law

- Since enthalpy is a state function, the change in enthalpy in going from some initial state to some final state is independent of the pathway. Thus, in going from a particular set of reactants to a particular set of products, the change in enthalpy is the same whether the reaction takes place in one step or a series of steps. This principle is known as Hess's law.
- Example: $N_2 + 2O_2 \rightarrow 2NO_2$ $\Delta H = 68$ kJ

  This reaction can be carried out in two distinct steps:

  1. $N_2 + O_2 \rightarrow \cancel{2NO}$ $\Delta H_1 = 180$ kJ
  2. $\cancel{2NO} + O_2 \rightarrow 2NO_2$ $\Delta H_2 = -112$ kJ

  $N_2 + 2O_2 \rightarrow 2NO_2$ $\Delta H = 68$ kJ

  Note: $\Delta H = \Delta H_1 + \Delta H_2$

  The two 2NO are cancelled out because one appears as a reactant and the other as a product.
- When using Hess's law, it is important to understand two characteristics of ΔH for a reaction:
  - If a reaction is reversed, the sign of ΔH is also reversed.
  - If the coefficients in a balanced equation are multiplied by an integer, the value of ΔH is multiplied by the same integer.
- Example: What is the standard enthalpy change for the reaction of lead(II) chloride with chlorine to give lead(IV) chloride?

  $PbCl_2(s) + Cl_2(g) \rightarrow PbCl_4(l)$

  The following is known:

  $Pb(s) + Cl_2(g) \rightarrow PbCl_2(s)$ $\Delta H = -359.4$ kJ

  $Pb(s) + 2Cl_2(g) \rightarrow PbCl_4(l)$ $\Delta H = -329.3$ kJ

Solution:

Reaction 1 has to be flipped so that $PbCl_2$ is a reactant. The value of ΔH is also changed from (-) to (+).

$PbCl_2(s) \rightarrow Pb(s) + Cl_2(g)$ $\Delta H = 359.4$ kJ

Reaction 2 does not need to be changed because $PbCl_4$ is already a product.

$Pb(s) + 2Cl_2(g) \rightarrow PbCl_4(l)$ $\Delta H = -329.3$ kJ

The two reactions are summed:

$PbCl_2(s) \rightarrow \cancel{Pb(s)} + Cl_2(g)$ $\Delta H = 359.4$ kJ

$\cancel{Pb(s)} + 2Cl_2(g) \rightarrow PbCl_4(l)$ $\Delta H = -329.3$ kJ

$\mathbf{PbCl_2(s) + Cl_2(g) \rightarrow PbCl_4(l)}$ $\mathbf{\Delta H = 30.1}$ **kJ**

Since there were two Cl_2 on the reactant side and one on the product side, (2-1 = 1) one Cl_2 remains as a reactant.

- Example: What is the standard enthalpy change for the reaction below?

  $2N_2(s) + 5O_2(g) \rightarrow 2N_2O_5(g)$

  The following is known:

  $H_2(g) + \frac{1}{2}O_2(g) \rightarrow H_2O(l)$ $\Delta H = -285.8$ kJ

  $N_2O_5(g) + H_2O(l) \rightarrow 2HNO_3(l)$ $\Delta H = -76.6$ kJ

  $\frac{1}{2}N_2(g) + 3/2\ O_2(g) + \frac{1}{2}H_2(g) \rightarrow HNO_3(l)$ $\Delta H = -174.1$ kJ

Solution:

Reaction 2 is flipped and multiplied by 2 in order to get 2 moles N_2O_5 on the product side. The sign of ΔH is changed from (-) to (+) because of the flip and the value is doubled because the coefficients are doubled.

$4HNO_3(l) \rightarrow 2N_2O_5(g) + 2H_2O(l)$ $\Delta H = 153.2$ kJ

Reaction 3 is multiplied by 4 in order to get 2 N_2 molecules. The ΔH value is also multiplied by 4.

$2N_2(g) + 6O_2(g) + 2H_2(g) \rightarrow 4HNO_3(l)$ $\Delta H = -696.4$ kJ

Reaction 1 has to be flipped and multiplied by 2 so that the H_2 can cancel the H_2 from reaction 3 above. ΔH is also doubled and the sign is changed from (-) to (+).

$2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$ $\Delta H = 571.6$ kJ

The reactions are summed:

$\cancel{4HNO_3}(l) \rightarrow 2N_2O_5(l) + \cancel{2H_2O(l)}$ $\Delta H = 153.2$ kJ

$2N_2(g) + 6O_2(g) + \cancel{2H_2}(g) \rightarrow \cancel{4HNO_3}(l)$ $\Delta H = -696.4$ kJ

$\cancel{2H_2O}(l) \rightarrow \cancel{2H_2}(g) + O_2(g)$ $\Delta H = 571.6$ kJ

$\mathbf{2N_2(s) + 5O_2(g) \rightarrow 2N_2O_5(g)}$ $\mathbf{\Delta H = 28.4}$ **kJ**

Homework Solve each of the following Hess's law problems. Show all work!

1. What is heat of reaction for the following reaction?

$C_{graphite}(s) \rightarrow C_{diamond}(s)$ **Answer: $\Delta H = +2$ kJ**

The following is known.

$C_{graphite}(s) + O_2(g) \rightarrow CO_2(g)$ $\Delta H = -394$ kJ
$C_{diamond}(s) + O_2(g) \rightarrow CO_2(g)$ $\Delta H = -396$ kJ

2. Calculate the heat of reaction for the following reaction:

$2NO_2(g) \rightarrow N_2O_4(g)$ **Answer: $\Delta H = -58.0$ kJ**

The following is known.

$N_2(g) + 2O_2(g) \rightarrow 2NO_2(g)$ $\Delta H = 67.7$ kJ
$N_2(g) + 2O_2(g) \rightarrow N_2O_4(g)$ $\Delta H = 9.7$ kJ

3. Calculate the heat of reaction for the following reaction:

$NO(g) + O(g) \rightarrow NO_2(g)$ **Answer: $\Delta H = -233$ kJ**

The following is known.

$2O_3(g) \rightarrow 3O_2(g)$ $\Delta H = -427$ kJ
$O_2(g) \rightarrow 2O(g)$ $\Delta H = 495$ kJ
$NO(g) + O_3(g) \rightarrow NO_2(g) + O_2(g)$ $\Delta H = -199$ kJ

4. Calculate the heat of reaction for the following reaction:

$C_6H_4(OH)_2(aq) + H_2O_2(aq) \rightarrow C_6H_4O_2(aq) + 2H_2O(l)$ **Answer: $\Delta H = -202.6$ kJ**

The following is known.

$C_6H_4(OH)_2(aq) \rightarrow C_6H_4O_2(aq) + H_2(g)$ $\Delta H = 177.4$ kJ
$H_2(g) + O_2(g) \rightarrow H_2O_2(aq)$ $\Delta H = -191.2$ kJ
$H_2(g) + \frac{1}{2}O_2(g) \rightarrow H_2O(g)$ $\Delta H = -241.8$ kJ
$H_2O(g) \rightarrow H_2O(l)$ $\Delta H = -43.8$ kJ

5. Calculate the heat of reaction for the following reaction:

$Ca(s) + C(s) + 3/2O_2(g) \rightarrow CaCO_3(s)$ **Answer: $\Delta H = -1207$ kJ**

The following is known.

$Ca(s) + 2C(s) \rightarrow CaC_2(s)$ $\Delta H = -62.8$ kJ
$CO_2(g) \rightarrow C(s) + O_2(g)$ $\Delta H = 393.5$ kJ
$CaCO_3(s) + CO_2(g) \rightarrow CaC_2(s) + 5/2O_2(g)$ $\Delta H = 1538$ kJ

6. Calculate the heat of reaction for the following reaction:

$2P(s) + 5Cl_2(g) \rightarrow 2PCl_5(s)$ **Answer: $\Delta H = -750.$ kJ**

The following is known.

$PCl_5(s) \rightarrow PCl_3(g) + Cl_2(g)$ $\Delta H = 87.9$ kJ
$2P(s) + 3Cl_2(g) \rightarrow 2PCl_3(g)$ $\Delta H = -574$ kJ

7. Use the information in the table to calculate the enthalpy of this reaction.

$C_2H_6(g) + 7/2\ O_2(g) \rightarrow 2CO_2(g) + 3H_2O(l)$

Reaction	$\Delta H_f°$, $kJ\cdot mol^{-1}$
$2C(s) + 3H_2(g) \rightarrow C_2H_6(g)$	–84.7
$C(s) + O_2(g) \rightarrow CO_2(g)$	–393.5
$H_2(g) + ½\ O_2(g) \rightarrow H_2O(l)$	–285.8

(A) –764 kJ (B) –1560 kJ (C) –1664 kJ (D) –3120 kJ (E) -595 kJ

8. Given these reactions:

$A \rightarrow 2B$ $\Delta H = 40$ kJ
$B \rightarrow C$ $\Delta H = -50$ kJ
$2C \rightarrow D$ $\Delta H = -20$ kJ

Calculate ΔH for the reaction: **$D + A \rightarrow 4C$**

(A) –100 kJ (B) –60 kJ (C) –40 kJ (D) 100 kJ (E) -30 kJ

9. $C_2H_6(g) + 7/2O_2(g) \rightarrow 2CO_2(g) + 3H_2O(g)$ $\Delta H° = –1427.7$ kJ

If the enthalpy of vaporization for $H_2O(l)$ is 44.0 kJ/mol, what is ΔH° for this reaction if $H_2O(l)$ is formed instead of $H_2O(g)$?

(A) –1295.7 kJ (B) –1383.7 kJ (C) –1471.7 kJ (D) –1559.7 kJ (E) -1515.7 kJ

10. Given the thermochemical equations:

$Br_2(l) + F_2(g) \rightarrow 2BrF(g)$ $\Delta H° = -188$ kJ
$Br_2(l) + 3F_2(g) \rightarrow 2BrF_3(g)$ $\Delta H° = -768$ kJ

Determine ΔH° for the reaction: **$BrF(g) + F_2(g) \rightarrow BrF_3(g)$** ΔH° = ?

(A) -956 kJ (B) -580 kJ (C) -290 kJ (D) -478 kJ (E) 580 kJ

11. Given these two standard enthalpies of formation:

Reaction 1: $S(s) + O_2(g) \rightleftharpoons SO_2\ (g)$ $\Delta H° = -295$ kJ/mole

Reaction 2: $S(s) + \frac{3}{2} O_2(g) \rightleftharpoons SO_3\ (g)$ $\Delta H° = -395$ kJ/mole

What is the heat of reaction for **$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$** under the same conditions?

(A) -1380 kJ/mole (B) -690. kJ/mole (C) -295 kJ/mole (D) -200. kJ/mole (E) -100. kJ/mole

12. Given the following information:

Reaction 1: $H_2(g) + ½\ O_2(g) \rightarrow H_2O(l)$ $\Delta H° = -286$ kJ
Reaction 2: $CO_2(g) \rightarrow C(s) + O_2(g)$ $\Delta H° = 394$ kJ
Reaction 3: $2CO_2(g) + H_2O(l) \rightarrow C_2H_2(g) + \frac{5}{2}\ O_2(g)$ $\Delta H° = 1300$ kJ

Find ΔH° for the reaction: **$C_2H_2\ (g) \rightarrow 2C(s) + H_2(g)$**

(A) -226 kJ (B) -113 kJ (C) 113 kJ (D) 226 kJ (E) 452 kJ

Additional Practice Problems

1. Calculate the ΔH° the following problems using Hess's law.

Given:

$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$	ΔH° = -23 kJ
$3Fe_2O_3 + CO \rightarrow 2Fe_3O_4 + CO_2$	ΔH° = -39 kJ
$Fe_3O_4 + CO \rightarrow 3FeO + CO_2$	ΔH° = +18 kJ

Find: **$FeO + CO \rightarrow Fe + CO_2$**

2. Calculate the ΔH° the following problems using Hess's law.

Given:

$P_4 + 6Cl_2 \rightarrow 4PCl_3$	ΔH° = -1225.6 kJ
$P_4 + 5O_2 \rightarrow P_4O_{10}$	ΔH° = -2967.3 kJ
$PCl_3 + Cl_2 \rightarrow PCl_5$	ΔH° = -84.2 kJ
$PCl_3 + \frac{1}{2} O_2 \rightarrow Cl_3PO$	ΔH° = -285.7 kJ

Find: **$P_4O_{10} + 6PCl_5 \rightarrow 10Cl_3PO$**

3. Calculate the ΔH° the following problems using Hess's law.

Given:

$Sr + \frac{1}{2} O_2 \rightarrow SrO$	ΔH° = -592 kJ
$SrO + CO_2 \rightarrow SrCO_3$	ΔH° = -234 kJ
$C + O_2 \rightarrow CO_2$	ΔH° = -394 kJ

Find: **$Sr + C + 3/2\ O_2 \rightarrow SrCO_3$**