SCH4U-C

12

Hess's Law

Introduction

In Lesson 11, you learned about alternative energy sources for heating and cooling your home. The focus of this lesson is again on alternative energy sources, but this time, you are going to consider alternative ways to power cars, including unconventional fuels. Most cars use gasoline (which is mostly octane, C_8H_{18}) as their fuel source. Other possible fossil fuels include natural gas (methane, CH_4) and propane (C_3H_8).

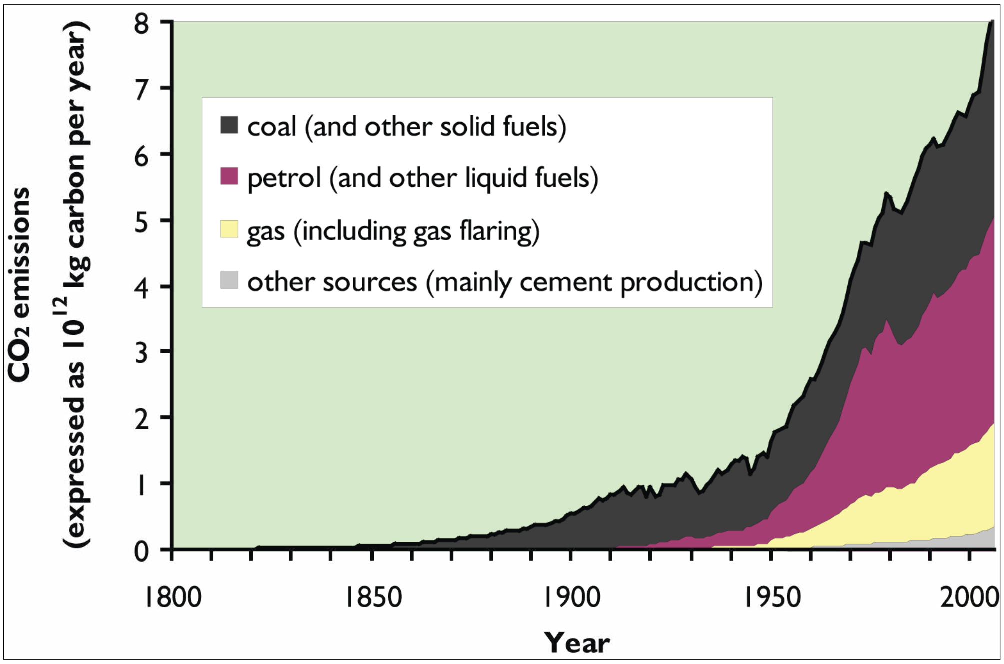

Figure 12.1: Annual global carbon dioxide emissions by source. The period covered is 1800 to 2006. Emissions are expressed in metric gigatonnes.

Source: http://commons.wikimedia.org/wiki/File:CO2-src.png

The combustion of fossil fuels results in the production of air pollutants because of impurities in the fuel and incomplete combustion of the fuel. However, only small quantities of these non-carbon pollutants are produced in comparison to the amount of carbon dioxide produced during combustion. Carbon dioxide is a greenhouse gas that traps heat within the earth's atmosphere, leading to global warming. Increased temperatures can cause the polar ice caps to melt. This raises global sea levels, causing the destruction of low-lying habitats. The increased atmospheric temperature also affects weather patterns. Storms become more intense, and parts of the earth may become wetter or drier, or they may become warmer or, surprisingly, colder. This is climate change.

Alternative means of powering cars, as well as other initiatives, are being developed in an effort to reduce the amount of carbon dioxide added to the atmosphere. You will learn about some of these proposals and initiatives in this lesson.

Planning Your Study

You may find this time grid helpful in planning when and how you will work through this lesson.

Suggested Timing For This Lesson (Hours)	
Hess's Law	¾
Activity: Hess's Law	¾
Heats of Formation	½
Case Study: Hybrid Cars	¼
Key Questions	1¼

What You Will Learn

After completing this lesson, you will be able to

- describe methods of reducing the production of greenhouse gases through policy initiatives and personal choices
- determine enthalpy changes for chemical reactions using Hess's law
- determine enthalpy changes for chemical reactions using heats of formation

Hess's Law

In Lesson 11, you learned about thermochemical equations and how ΔH is calculated using calorimetry techniques. In this lesson, you will learn about Hess's law, which is used to calculate ΔH values for reactions that are not measured directly through experiments and observations.

At times it may be necessary to alter a thermochemical equation. For example:

$Na_{(s)} + ½Cl_{2(g)} \rightarrow NaCl_{(s)}$ $\Delta H = -411.2$ kJ

But if the equation is written without fractional coefficients, by doubling the whole equation, it would appear as:

$2Na_{(s)} + Cl_{2(g)} \rightarrow 2NaCl_{(s)}$ $\Delta H = -822.4$ kJ

Notice that the value of ΔH has doubled because two moles of sodium chloride are produced.

This holds true for decomposition reactions, where a compound is broken down into elements or smaller compounds. Consider the pair of equations representing the decomposition of hydrogen peroxide:

$H_2O_{2(l)} \rightarrow H_2O_{(l)} + ½O_{2(g)}$ $\Delta H = +187.8$ kJ

$2H_2O_{2(l)} \rightarrow 2H_2O_{(l)} + O_{2(g)}$ $\Delta H = +375.6$ kJ

Combustion reactions work the same way. Check out the example for the combustion of octane, the key ingredient in gasoline:

$C_8H_{18(l)} + 25/2O_{2(g)} \rightarrow 8CO_{2(g)} + 9H_2O_{(g)}$ $\Delta H = -5450$ kJ

$2C_8H_{18(l)} + 25O_{2(g)} \rightarrow 16CO_{2(g)} + 18H_2O_{(g)}$ $\Delta H = -10\,900$ kJ

Calorimetry is often used to determine ΔH values. However, it is not always possible to use this method. Some reactions happen too slowly or too quickly to measure all of the heat changes in the surroundings. Chemists had to come up with alternative means of determining ΔH.

Germain Hess, a chemist, proposed Hess's law to calculate ΔH values for reactions that could not be measured through calorimetry by using ΔH values from other related reactions.

Consider the following example. A chemist wants to determine the ΔH value for the synthesis of carbon dioxide from carbon monoxide and an oxygen atom.

$CO_{(g)} + ½O_{2(g)} \rightarrow CO_{2(g)}$ $\Delta H = ?$ kJ

This is known as the *target equation*. In some reactions, the ΔH value cannot be determined directly through calorimetry. However, the chemist may know the ΔH values for some closely related reactions, such as:

Given #1: $C_{(s)} + O_{2(g)} \rightarrow CO_{2(g)}$ $\Delta H = -393.5$ kJ

and

Given #2: $C_{(s)} + ½O_{2(g)} \rightarrow CO_{(g)}$ $\Delta H = -110.5$ kJ

These are the *given* or *known equations* and they can be manipulated to yield the target equation.

Manipulations include reversing the equation so that the reactants become the products and the products become the reactants. If you reverse the equation, you must also reverse the sign of the ΔH value. It is also possible to multiply or divide the equation by a certain number to alter the coefficients. The ΔH value would then have to be multiplied or divided by the same number.

Recall from the lesson dealing with redox equations how half-reactions were added to produce the overall reaction. Hess's Law utilizes the same principle. We will find thermochemical equations, manipulate them as required, and add them together with the objective of producing the "target" equation (the desired equation).

In this situation, we wish to determine the ΔH for the equation

$CO_{(g)} + ½O_{2(g)} \rightarrow CO_{2(g)}$ This will be called our target equation.

The target has two compounds in it; 1 mole of CO on the left side and 1 mole of CO_2 on the right side. Elements such as O_2 can be ignored because the process we follow will take care of elements for us. Let's now find equations that, when added, will give the target.

If we are to add equations to produce that target, then we need an equation that has 1 mole of CO on its left side. The given #2 equation will work for that if we reverse it.

$CO_{(g)} \rightarrow C_{(s)} + ½O_{2(g)}$ $\Delta H = +110.5$ kJ (sign was changed) call this equation (3)

We also need an equation that has 1 mole of CO_2 on its right side (the target has that). The given #1 will work for that just the way it was written.

$C_{(s)} + O_{2(g)} \rightarrow CO_{2(g)}$ $\Delta H = -393.5$ kJ equation (1)

If we now add the two equations, (3) and (1), along with their associated ΔH values, we get

$CO_{(g)} + C_{(s)} + O_{2(g)} \rightarrow C_{(s)} + ½O_{2(g)} + CO_{2(g)}$ $\Delta H = 110.5 \text{ kJ} + (-393.5 \text{ kJ})$

Simplifying this, the $C_{(s)}$ cancels and the O_2 is collected to one side.

$CO_{(g)} + ½O_{2(g)} \rightarrow CO_{2(g)}$ $\Delta H = -283.0$ kJ

We have produced our target by adding just two equations. Frequently, more than two equations are required, depending on the complexity of the target. It does not matter how many equations you use or which equations you find to use, as long as, when you add them, the desired equation (the target) is produced.

This is known as the Hess's law method. This method uses given equations for related reactions to determine the ΔH for the target reaction. The following steps summarize the method:

Step 1: Write out the target equation and the known (given) equations, noting the identities and coefficients of reactants and products.

Step 2: Look at each of the given equations individually and compare them to the target equation. Concentrate on compounds in the target. Ignore elements such as $O_{(g)}$ or $C_{(s)}$

Step 3: If necessary, reverse a given equation so that a compound is on the same side as in the target equation. Reverse the sign of the ΔH value, if you reverse an equation.

Step 4: If necessary, multiply or divide a given equation by an appropriate number to have the same number of moles of the compound as the target equation. Multiply or divide the ΔH value by the same number.

Step 5: When you have finished all of your manipulations of the given equations and accounted for every compound in the target equation, add your equations and simplify.

Step 6: Check to make sure that what you have left is the target equation.

Step 7: Add the individual ΔH values together to determine the ΔH value for the target equation.

Now, notice how the above steps are used to solve the following examples.

Example

Given the following reactions,

$H_{2(g)} + Cl_{2(g)} \rightarrow 2HCl_{(g)}$ $\Delta H = -185.0$ kJ

$H_{2(g)} + ½O_{2(g)} \rightarrow H_2O_{(g)}$ $\Delta H = -241.8$ kJ

determine the ΔH for this target equation:

$4HCl_{(g)} + O_{2(g)} \rightarrow 2Cl_{2(g)} + 2H_2O_{(g)}$

Solution

Target: $4HCl_{(g)} + O_{2(g)} \rightarrow 2Cl_{2(g)} + 2H_2O_{(g)}$ $\Delta H = ?$ kJ

Ignore elements $O_{2(g)}$ and $Cl_{2(g)}$. The procedure will take care of these when we add. Therefore, concentrate on the two compounds, 4HCl on the left side and $2H_2O$ on the right side. You could underline these in the target.

First, reverse the first given equation so that HCl is on the left side, as required in the target.

$2HCl_{(g)} \rightarrow \cancel{H_{2(g)}} + Cl_{2(g)}$ $\Delta H = +185.0$ kJ

Then, double the reversed equation because there are four, not two, moles of HCl in the target:

$4HCl_{(g)} \rightarrow \cancel{2H_{2(g)}} + 2Cl_{2(g)}$ $\Delta H = +370.0$ kJ

Finally, double the second equation (H_2O has a coefficient of 2):

$\cancel{\mathbf{2H_{2(g)}}} + O_{2(g)} \rightarrow 2H_2O_{(g)}$ $\Delta H = -483.6$ kJ

Add the newly created equations together and cancel out the items that appear as both reactants and products. The newly created equations are shown below.

$4HCl_{(g)} \rightarrow \cancel{\mathbf{2H_{2(g)}}} + 2Cl_{2(g)}$ $\Delta H = +\ 370.0$ kJ

$\cancel{\mathbf{2H_{2(g)}}} + O_{2(g)} \rightarrow 2H_2O_{(g)}$ $\Delta H = -483.6$ kJ

Check to make sure that you have reached the target equation. Add up the individual ΔH values to determine the ΔH value for the target:

$4HCl_{(g)} + O_{2(g)} \rightarrow 2Cl_{2(g)} + 2H_2O_{(g)}$ $\Delta H = -113.6$ kJ

Notice how the elements, oxygen and chlorine, appeared when the addition was completed.

Example

Ethanol reacts with oxygen to produce ethanoic acid and water. (This is the reaction that turns the alcohol in wine into vinegar.) What is the ΔH value for this reaction if the ΔH for the complete combustion of ethanol is –1369 kJ/(mol of ethanol) and the ΔH value for the complete combustion of ethanoic acid is –875 kJ/(mol of ethanoic acid)?

Solution

In this example, you have to write and balance your own thermochemical equations from the information provided. You will have to refer back to earlier lessons on organic chemistry to come up with some of the formulas. Complete combustion means that the fuel reacts with sufficient oxygen to produce carbon dioxide and water.

Target: $C_2H_5OH_{(l)} + O_{2(g)} \rightarrow CH_3COOH_{(l)} + H_2O_{(l)}$ $\Delta H = ?$ kJ

Given #1: Combustion of ethanol

$$C_2H_5OH_{(l)} + 3O_{2(g)} \rightarrow 2CO_{2(g)} + 3H_2O_{(l)} \quad \Delta H = -1369 \text{ kJ}$$

Given # 2: Combustion of ethanoic acid (acetic acid)

$$CH_3COOH_{(l)} + 2O_{2(g)} \rightarrow 2CO_{2(g)} + 2H_2O_{(l)} \quad \Delta H = -875 \text{ kJ}$$

The element, $O_{2(g)}$, in the target is ignored.

Given #1 has $1C_2H_5OH_{(l)}$ on the left side (same as target), so that given will be used as is.

Given #2 will be reversed to have $1CH_3COOH_{(l)}$ on the right side (like the target).

We will write down these two manipulations of the given equations and add them, even though we have not considered the $H_2O_{(l)}$ in the target. Notice that both given equations have water in them. Hopefully the water will work out for us.

$C_2H_5OH_{(l)} + 3O_{2(g)} \rightarrow 2CO_{2(g)} + 3H_2O_{(l)} \quad \Delta H = -1369$ kJ

$2CO_{2(g)} + 2H_2O_{(l)} \rightarrow CH_3COOH_{(l)} + 2O_{2(g)} \quad \Delta H = +875$ kJ (sign is changed)

Adding…

$C_2H_5OH_{(l)} + O_{2(g)} \rightarrow CH_3COOH_{(l)} + H_2O_{(l)} \quad \Delta H = -494$ kJ

Notice that the water *did* work out for us. If it had not, we would look for a third given equation dealing with water.

Support Question

Be sure to try the Support Questions on your own before looking at the suggested answers provided.

37. Sucrose ferments, producing ethanol, according to the following equation:

$C_{12}H_{22}O_{11(s)} + H_2O_{(l)} \rightarrow 4C_2H_5OH_{(l)} + 4CO_{2(g)}$

Calculate the ΔH for this reaction, given that the ΔH value for the complete combustion of sucrose is –5645 kJ/mol, and the ΔH value for the complete combustion of ethanol is –1369 kJ/mol.

Suggested answer

Heats of Formation

Another method of determining the enthalpy change for reactions is by using the heats of formation, ΔH_f values, for the reactants and products. A formation reaction is a very specific type of reaction. It involves the formation of one mole of a compound from its elements in their natural state only. Their "natural state" means their molecular and physical state (a solid, liquid, or gas), as found in the laboratory or in the real world.

A few elements will never be found as lone atoms—they always exist as diatomic molecules: hydrogen (H_2), oxygen (O_2), fluorine (F_2), bromine (Br_2), iodine (I_2), nitrogen (N_2) and chlorine (Cl_2). All the rest of the elements exist naturally as single atoms. When these elements are included in formation reactions, they must be written in their natural, diatomic state. In other words, you should write H_2 rather than H.

The following are potential formation reactions for sodium hydroxide. Only one is written correctly as a formation reaction. Can you pick out the correct one? What is wrong with the other four?

1. $H_{2(g)} + O_{2(g)} + 2Na_{(s)} \rightarrow 2NaOH_{(s)}$
2. $H_{(g)} + O_{(g)} + Na_{(s)} \rightarrow NaOH_{(s)}$
3. $½Na_2O_{(s)} + ½H_2O_{(l)} \rightarrow NaOH_{(s)}$
4. $½H_{2(g)} + ½O_{2(g)} + Na_{(s)} \rightarrow NaOH_{(s)}$
5. $Na_2O_{(s)} + H_2O_{(g)} \rightarrow 2NaOH_{(s)}$

The fourth one is the only correct one. It shows hydrogen and oxygen as diatomic gases (their natural state), and has one mole of sodium hydroxide as the product. The first is close: the elements are in their natural state, but the equation has been balanced so that there are two moles of product instead of one. In the second one, hydrogen and oxygen should be diatomic (their natural state). The third and the fifth use compounds, not elements, to form sodium hydroxide. The fifth also has two moles of compound instead of one, and NaOH is not forming from its basic elements.

Over the years, chemists have determined the $\Delta H°_f$ values for many formation reactions. These are listed in the table provided on the next page. They were determined under standard conditions, which is why the "°" appears with the $\Delta H°_f$. The $\Delta H°_f$ value is not known for every compound. The following table shows some common $\Delta H°_f$ values—the ones you will be using in this part of the lesson, and in the Support Questions, Key Questions, and Final Test. You do not have to memorize these values.

Table 12.1: The heats of formation ($\Delta H°_f$) values for selected compounds

Compound	$\Delta H°_f$ (kJ/mol)
$CH_{4(g)}$	–74.4
$C_2H_{6(g)}$	–83.8
$C_3H_{8(g)}$	–104.7
$C_4H_{10(l)}$	–125.6
$Na_2CO_{3(s)}$	–1130.8
$CO_{2(g)}$	–393.5
$H_2O_{(l)}$	–285.8
$H_2O_{(g)}$	–241.8
$C_6H_{6(l)}$	+49.0

How are these values used to calculate the ΔH for a chemical reaction? The equation that you use is:

$$\Delta H = \Sigma\Delta H°_{f\,(\text{products})} - \Sigma\Delta H°_{f\,(\text{reactants})}$$

In other words, this means that the enthalpy change for a reaction is equal to the sum (Σ) of the $\Delta H°_f$ values of the products minus the sum (Σ) of the $\Delta H°_f$ values of the reactants. You look up the values on the table, substitute them into the equation, and solve the equation. Note that this method will give you the same result as the previous method that you learned.

Example

What is the ΔH for the complete combustion of butane to water vapour and carbon dioxide?

Solution

Step 1: Start off by writing down the balanced equation:

$C_4H_{10(l)} + 6.5O_{2(g)} \rightarrow 4CO_{2(g)} + 5H_2O_{(g)}$

Step 2: Then, substitute heats of formation values into the equation from the table, remembering to multiply by any coefficients:

$\Delta H = \Sigma\Delta H°_{f\,(products)} - \Sigma\Delta H°_{f\,(reactants)}$

$\Delta H = [4 \text{ mol } \Delta H°_{f(CO2)} + 5 \text{ mol } \Delta H°_{f(H2O)}] - [1 \text{ mol } \Delta H°_{f(C4H10)}]$

$= [4 \text{ mol } (-393.5 \text{ kJ/mol}) + 5 \text{ mol } (-241.8 \text{ kJ/mol})] - [1 \text{ mol } (-125.6 \text{ kJ/mol})]$

$= -2657.4 \text{ kJ}$

The enthalpy change for the given reaction for the combustion of butane is –2657.4 kJ.

Note that oxygen did not appear in the substitution and is not listed in the table. That is because oxygen is already in its natural state and does not have to be "formed." As well, check the state of water carefully. It can exist as both a vapour and a liquid, and each has a different $\Delta H°_f$ value.

This method of determining ΔH is related to Hess's law. If the combustion of butane is the target equation and the various formation reactions are known or given, you can see the connection.

Target: $C_4H_{10(l)} + 6.5O_{2(g)} \rightarrow 4CO_{2(g)} + 5H_2O_{(g)}$

$C_{(s)} + O_{2(g)} \rightarrow CO_{2(g)}$ $\Delta H = -393.5$ kJ (1)

$H_{2(g)} + ½O_{2(g)} \rightarrow H_2O_{(g)}$ $\Delta H = -241.8$ kJ (2)

$4C_{(s)} + 5H_{2(g)} \rightarrow C_4H_{10(l)}$ $\Delta H = -125.6$ kJ (3)

$\cancel{4C_{(s)}} + 4O_{2(g)} \rightarrow 4CO_{2(g)}$ $\Delta H = -1574$ kJ (1) × 4

$\cancel{5H_{2(g)}} + 2.5O_{2(g)} \rightarrow 5H_2O_{(g)}$ $\Delta H = -1209$ kJ (2) × 5

$C_4H_{10(l)} \rightarrow \cancel{4C_{(s)}} + \cancel{5H_{2(g)}}$ $\Delta H = +125.6$ kJ (3) reversed

Add the above three equations.

$C_4H_{10(l)} + 6.5O_{2(g)} \rightarrow 4CO_{2(g)} + 5H_2O_{(g)}$ $\Delta H = -2657.4$ kJ

Notice how the units (mol and kJ/mol) were included within the calculations. Units are critical to all problem solutions and must always be included. Note also that the answer would contain one decimal place because all of the heats of formation being used had one decimal. We are just adding and subtracting values in this problem so decimal places are considered, not sig-figs.

Support Questions

38. Write formation equations for the following compounds:

a) $NaHCO_{3(s)}$

b) $Ca(OH)_{2(s)}$

c) $NH_4Cl_{(s)}$ Suggested answer

39. Benzene ($C_6H_{6(l)}$) undergoes complete combustion. Assume that liquid water is produced.

a) Write a balanced equation for the complete combustion of 1 mole of liquid benzene.

b) Using heats of formation values from Table 12.1, determine the enthalpy change for the reaction written in a). Write the thermochemical equation two ways. Suggested answer

Case Study: Hybrid Cars

The car that you choose to drive, or whether you drive at all, has a great impact on the environment. Two alternative means of powering cars are the fuel cell (which was described in Lesson 10) and the gasoline-electric hybrid.

Much of the fuel-cell technology that is used today resulted from the inventions of Geoffrey Ballard, a Canadian scientist. The fuel cell uses hydrogen as its fuel and produces only water vapour as a waste product—there are no greenhouse gases or other pollutants. Ballard's fuel cells are used in urban transit buses in Vancouver and in a number of European cities. Ballard's fuel cells are also used in forklifts in warehouses, where the production of poisonous carbon monoxide is a concern, as well as for generating electricity in remote locations that have a ready source of hydrogen-rich compounds (such as methane). Ballard believed that personal cars would not be powered by fuel cells until there was some kind of incentive to persuade people to give up fossil-fuel-powered cars. Fuel-cell technology is expensive initially, but pays for itself when fuel and environmental savings are factored in. Because hydrogen is difficult to handle, store, and transport, there are no mass-produced fuel-cell-powered cars for sale in Canada.

The other alternative to fossil-fuel-powered cars is the hybrid car. These are becoming increasingly common on Canada's roads. Currently, there are 12 different models from 8 different car manufacturers available for sale in Canada. As of 2010, the federal and provincial governments have offered tax rebates of up to $4000 to people who purchase hybrid cars. Insurance companies have provided a discount on premiums for owners of hybrid cars, and manufacturers have included extended warranties in the price of these cars.

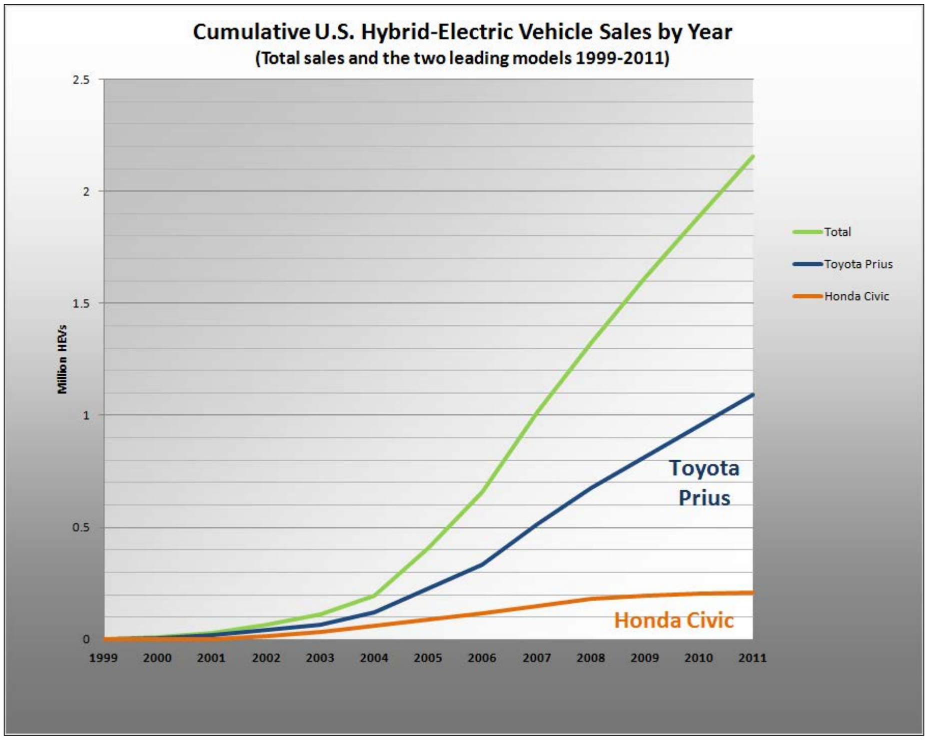

Figure 12.2: Graph showing historical trend of cumulative sales of US hybrids series 1999–2009. Data series taken from Alternative Fuels and Advanced Vehicles Data Center (US DoE).

Source: http://commons.wikimedia.org/wiki/File:Cumulative_US_HEV_Sales_by_year_1999_2009.png

Careers in Chemistry

Margaret-Ann Armour
Birthplace: Scotland; Canadian citizen and named to the Order of Canada 2006

Photo of Dr. Armour

***In Focus*—Margaret-Ann Armour (Department of Chemistry: University of Alberta)**

"We are pleased to present to you one of our distinguished colleagues, Margaret-Ann Armour, who has been actively engaged in various aspects of science education and research. An invaluable member of our department, she is internationally recognized for her commitment to advancing the role of women in science and engineering, and is the recipient of numerous national and international awards."

Biographical Sketch

Margaret-Ann Armour was born in Scotland and educated at Edinburgh University, where she obtained Bachelor and Master of Science degrees. She worked as a research chemist in the paper-making industry for five years before coming to the University of Alberta in Edmonton where, in 1970, she graduated with a Ph.D. in physical organic chemistry. From 1979–1989 she was supervisor of the undergraduate organic chemistry laboratories in the Chemistry Department and since 1989, has served as Assistant Chair.

Her research has been into the development and testing of methods for recycling or disposing of small quantities of waste and surplus chemicals. The results are described in "Hazardous Laboratory Chemicals Disposal Guide" published by CRC Press (third edition, 2003). Dr. Armour has presented talks on the work to many groups of small quantity generators of hazardous waste in North America and throughout Asia. Dr. Armour is the author or co-author of over 100 proceedings and papers on chemical education, hazardous waste disposal and women in science. She serves on the Board of SHAD International and of the Pacific Basin Consortium for Hazardous Waste Research and Management. She has been a Scientific Advisor to the Asian Association for Academic Activity on Waste Management.

Since 1984, Dr. Armour has been Vice-Chair and Convenor of WISEST, a committee of the Vice-President, Research, at the University of Alberta on Women in Scholarship, Engineering, Science and Technology with a mandate to take action to increase the proportion of women in decision-making roles in the sciences and engineering.

Source: Text and photo, Department of Chemistry, University of Alberta.

Key Questions

Now work on your Key Questions in the online submission tool. You may continue to work at this task over several sessions, but be sure to save your work each time. When you have answered all the unit's Key Questions, submit your work to the ILC.

45. You have been asked to write an opinion for an environmental magazine about the benefits of purchasing a hybrid vehicle for day-to-day driving. You can use some of the information in the lesson to help get you started, but you will have to do some additional research at a library or at home, on the Internet. You should use at least two sources, which you must list in a properly formatted bibliography. Your answer to this Key Question should be about 500 words long.

Your writing should include the following:

- An explanation of the operation of a hybrid car, including how it reduces greenhouse-gas emissions **(3 marks)**
- The benefits of hybrid cars **(3 marks)**
- The concerns about hybrid cars **(2 marks)**
- At least three detailed explanations to support your opinion on whether you believe that the benefits outweigh the concerns **(3 marks)**
- At least two sources, which you must list in a properly formatted "references" section **(2 marks)**
- Communication skills, such as proper spelling and full sentences, which will add to your marks **(2 marks)**

46. Using Hess's law, calculate the ΔH value for the following reaction: **(8 marks)**

$FeO_{(s)} + CO_{(g)} \rightarrow Fe_{(s)} + CO_{2(g)}$

Use these three reactions:

$Fe_2O_{3(s)} + 3CO_{(g)} \rightarrow 2Fe_{(s)} + 3CO_{2(g)}$ $\Delta H = -25.0$ kJ

$3Fe_2O_{3(s)} + CO_{(g)} \rightarrow 2Fe_3O_{4(s)} + CO_{2(g)}$ $\Delta H = -47.0$ kJ

$Fe_3O_{4(s)} + CO_{(g)} \rightarrow 3FeO_{(s)} + CO_{2(g)}$ $\Delta H = +38.0$ kJ

47. Sodium bicarbonate ($NaHCO_3$) is often used in the kitchen to extinguish fires. When heated, it decomposes into sodium carbonate, water vapour, and carbon dioxide. The ΔH for the reaction of 1 mole of sodium bicarbonate is +64.6 kJ.

a) Write a balanced thermochemical equation for this reaction. **(2 marks)**

b) Using the enthalpies of formation, calculate the enthalpy of formation of sodium bicarbonate. **(5 marks)**

This is the last lesson in Unit 3. When you have completed all the Key Questions, submit your work to the ILC. A teacher will mark it and you will receive your results online.

Periodic Table

Atomic Number → 6
Symbol → **C**
Name → Carbon
Average Atomic Mass → 12.011
4, −4, 2 ← Common Oxidation States

Period	Group 1 IA	Group 2 IIA	Group 3 IIIB	Group 4 IVB	Group 5 VB	Group 6 VIB	Group 7 VIIB	Group 8	Group 9 VIIIB	Group 10	Group 11 IB	Group 12 IIB	Group 13 IIIA	Group 14 IVA	Group 15 VA	Group 16 VIA	Group 17 VIIA	Group 18 VIIIA
1	1 **H** Hydrogen 1.00794 1, −1																	2 **He** Helium 4.002602
2	3 **Li** Lithium 6.941 1	4 **Be** Beryllium 9.012182 2											5 **B** Boron 10.811 3	6 **C** Carbon 12.011 4, −4, 2	7 **N** Nitrogen 14.00674 3, −3, 5	8 **O** Oxygen 15.9994 −2	9 **F** Fluorine 18.9984032 −1	10 **Ne** Neon 20.1797
3	11 **Na** Sodium 22.989768 1	12 **Mg** Magnesium 24.3050 2											13 **Al** Aluminum 26.981539 3	14 **Si** Silicon 28.0855 4	15 **P** Phosphorus 30.973762 5, −3, 3	16 **S** Sulfur 32.066 6, −2, 2	17 **Cl** Chlorine 35.4527 −1, 1, 3	18 **Ar** Argon 39.948
4	19 **K** Potassium 39.0983 1	20 **Ca** Calcium 40.078 2	21 **Sc** Scandium 44.955910 3	22 **Ti** Titanium 47.88 4, 3	23 **V** Vanadium 50.9415 5, 4, 3	24 **Cr** Chromium 51.9961 3, 2, 6	25 **Mn** Manganese 54.93805 2, 3, 4	26 **Fe** Iron 55.847 2, 3	27 **Co** Cobalt 58.93320 2, 3	28 **Ni** Nickel 58.6934 2, 3	29 **Cu** Copper 63.546 2, 1	30 **Zn** Zinc 65.39 2	31 **Ga** Gallium 69.723 3	32 **Ge** Germanium 72.61 4	33 **As** Arsenic 74.92159 3, −3, 5	34 **Se** Selenium 78.96 4, −2, 6	35 **Br** Bromine 79.904 −1, 1, 5	36 **Kr** Krypton 83.80
5	37 **Rb** Rubidium 85.4678 1	38 **Sr** Strontium 87.62 2	39 **Y** Yttrium 88.90585 3	40 **Zr** Zirconium 91.224 4	41 **Nb** Niobium 92.90638 5, 3	42 **Mo** Molybdenum 95.94 6, 5, 4	43 **Tc** Technetium (97.90772) 7	44 **Ru** Ruthenium 101.07 3, 4, 6	45 **Rh** Rhodium 102.90550 3, 2, 4	46 **Pd** Palladium 106.42 2, 4	47 **Ag** Silver 107.8682 1	48 **Cd** Cadmium 112.411 2	49 **In** Indium 114.818 3	50 **Sn** Tin 118.710 4, 2	51 **Sb** Antimony 121.757 3, −3, 5	52 **Te** Tellurium 127.60 4, −2, 6	53 **I** Iodine 126.90447 −1, 1, 5	54 **Xe** Xenon 131.29
6	55 **Cs** Cesium 132.90543 1	56 **Ba** Barium 137.327 2	57 **La** Lanthanum 138.9055 3	72 **Hf** Hafnium 178.49 4	73 **Ta** Tantalum 180.9479 5	74 **W** Tungsten 183.84 6, 5, 4	75 **Re** Rhenium 186.207 7, −1, 6	76 **Os** Osmium 190.23 4, 2, 3	77 **Ir** Iridium 192.22 4, 2, 3	78 **Pt** Platinum 195.08 4, 2	79 **Au** Gold 196.96654 3, 1	80 **Hg** Mercury 200.59 2, 1	81 **Tl** Thallium 204.3833 1, 3	82 **Pb** Lead 207.2 2, 4	83 **Bi** Bismuth 208.98037 3, 5	84 **Po** Polonium (208.9824) 4, 2	85 **At** Astatine (209.9871) −1, 1, 3	86 **Rn** Radon (222.01761)
7	87 **Fr** Francium (223.0197) 1	88 **Ra** Radium (226.0254) 2	89 **Ac** Actinium (227.0278) 3	104 **Rf** Rutherfordium (261.11)	105 **Db** Dubnium (262.114)	106 **Sg** Seaborgium (263.118)	107 **Bh** Bohrium (262.12)	108 **Hs** Hassium (265)	109 **Mt** Meitnerium (266)	110 **Ds** Darmstadtium (269)	111 **Rg** Roentgenium (272)	112 **Uub** Ununbium (275)	113 **Uut** Ununtrium (278)	114 **Uuq** Ununquadium (282)	115 **Uup** Ununpentium	116 **Uuh** Ununhexium	117 **Uus** Ununseptium	118 **Uuo** Ununoctium

58 **Ce** Cerium 140.115 3, 4	59 **Pr** Praseodymium 140.90765 3, 4	60 **Nd** Neodymium 144.24 3	61 **Pm** Promethium (144.9127) 3	62 **Sm** Samarium 150.36 3, 2	63 **Eu** Europium 151.965 3, 2	64 **Gd** Gadolinium 157.25 3	65 **Tb** Terbium 158.92534 3, 4	66 **Dy** Dysprosium 162.50 3	67 **Ho** Holmium 164.93032 3	68 **Er** Erbium 167.26 3	69 **Tm** Thulium 168.93421 3, 2	70 **Yb** Ytterbium 173.04 3, 2	71 **Lu** Lutetium 174.967 3
90 **Th** Thorium 232.0381 4	91 **Pa** Protactinium 231.03588 5, 4	92 **U** Uranium 238.0289 6, 5, 4	93 **Np** Neptunium (237.0482) 5, 4, 3	94 **Pu** Plutonium (244.0642) 4, 3, 5	95 **Am** Americium (243.0614) 3, 4, 5	96 **Cm** Curium (247.0703) 3	97 **Bk** Berkelium (247.0703) 3, 4	98 **Cf** Californium (251.0796) 3	99 **Es** Einsteinium (252.083)	100 **Fm** Fermium (257.0951)	101 **Md** Mendelevium (258.10)	102 **No** Nobelium (259.1009)	103 **Lr** Lawrencium (262.111)