Chapter 6

Quantities in Chemical Reactions

1

Introduction

- How can we predict amounts of reactants and products in a reaction, such as that in an internal combustion engine?
- How can we predict the amount of heat generated or absorbed during a reaction?

Figure 6.1

2

Internal Combustion Engine

- In an ICE, octane burns with oxygen to produce hot gases that push against a piston to do work.
- The amount of oxygen that reacts is dependent upon the amount of octane that burns.
- The amount of energy produced also depends on the amount of octane that reacts.

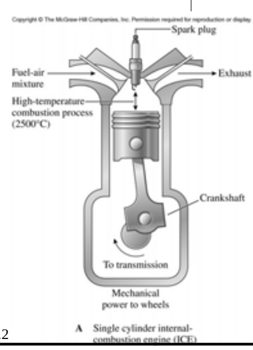


Figure 6.2

Chapter 6 Topics

1. The meaning of a balanced equation
2. Mole-mole conversions
3. Mass-mass conversions
4. Limiting reactants
5. Percent yield
6. Energy changes

4

6.1 The Meaning of a Balanced Equation

- What does a balanced equation tell us about the relative amounts of reactants and products?

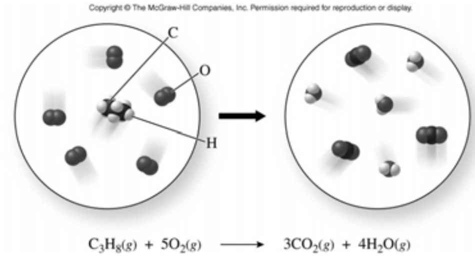


Figure 6.4

5

Amounts of Reactants and Products

$C_3H_8(g)$ +	$5O_2(g)$ →	$3CO_2(g)$ +	$4H_2O(g)$
1 molecule	5 molecules	3 molecules	4 molecules
2 molecules			
100 molecules			
6.022×10^{23} molecules			
1.000 mole			
0.40 mole			

6

Amounts of Reactants and Products

TABLE 6.1 Relationships between Reactants and Products

$C_3H_8(g)$ +	$5O_2(g)$ $\longrightarrow$	$3CO_2(g)$ +	$4H_2O(g)$
1 molecule	5 molecules	3 molecules	4 molecules
2 molecules	10 molecules	6 molecules	8 molecules
100 molecules	500 molecules	300 molecules	400 molecules
6.022×10^{23} molecules	$5 \times (6.022 \times 10^{23})$ molecules	$3 \times (6.022 \times 10^{23})$ molecules	$4 \times (6.022 \times 10^{23})$ molecules
1.000 mol	5.000 mol	3.000 mol	4.000 mol

The process of determining the amount of a reactant or product from another reactant or product in a reaction is called stoichiometry.

8

Mole Ratios

$C_3H_8(g) + 5O_2(g) \rightarrow 3CO_2(g) + 4H_2O(g)$

- **A mole ratio is used to relate the number of moles of one reactant or product to another.**
- **Mole ratios are obtained from the coefficients in the balanced equation.**
- **For example, the mole ratio of O_2 to C_3H_8 is 5:1 or:**

9

Mole Ratios

$C_3H_8(g) + 5O_2(g) \rightarrow 3CO_2(g) + 4H_2O(g)$

- **The mole ratio of O_2 to C_3H_8 allows us to calculate the amount of O_2 that will react with any amount of C_3H_8 that reacts.**
- **If 0.40 mol C_3H_8 reacts:**

10

Mole Ratios

$C_3H_8(g) + 5O_2(g) \rightarrow 3CO_2(g) + 4H_2O(g)$

- **What is the mole ratio for determining the moles of CO_2 that will be produced when 2.3 mol O_2 reacts?**
- **How many moles of CO_2 will be produced?**

11

Mole Ratios

$2Al(s) + 3Cl_2(g) \rightarrow 2AlCl_3(g)$

- **How many moles of Cl_2 are required to prepare 0.62 mol $AlCl_3$?**

12

6.2 Mass-Mass Conversions

- **$2Na(s) + Cl_2(g) \rightarrow 2NaCl(s)$**
- **What mass of chlorine gas is required to react with 9.20 grams of sodium?**
  - **We don't measure reactants and products in moles, but we commonly measure their mass.**
  - **The balanced equation does not tell us a mass relationship.**
  - **How do we convert grams of reactant or product to moles?**

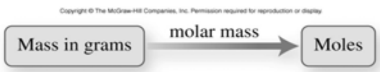
13

Mass-Mass Conversions

$2Na(s)$ + $Cl_2(g)$ → $2NaCl(s)$

(9.20 g Na)

1. **We convert grams to moles using molar mass:**



For a review, see Section 4.2

14

Mass-Mass Conversions

$2Na(s)$ + $Cl_2(g)$ → $2NaCl(s)$

(9.20 g Na)

(0.400 mol)

2. **Next we relate moles of Cl_2 to moles of Na using the mole ratio:**

15

Mass-Mass Conversions

$2Na(s)$ + $Cl_2(g)$ → $2NaCl(s)$

(9.20 g Na)

(0.400 mol Na) (0.200 mol Cl_2)

3. **The last step is to convert moles of Cl_2 to grams using the molar mass of Cl_2:**

16

Mass-Mass Conversions

$2Na(s)$ + $Cl_2(g)$ → $2NaCl(s)$

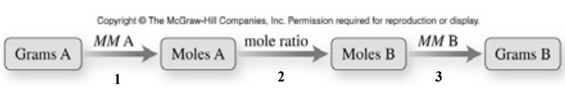
(9.20 g Na) (14.2 g Cl_2)

(0.400 mol Na) (0.200 mol Cl_2)

3. **The last step is to convert moles of Cl_2 to grams using the molar mass of Cl_2:**

17

Steps for Mass-Mass Conversions



18

Mass-Mass Conversions

$2Na(s)$ + $Cl_2(g)$ → $2NaCl(s)$

- **What mass of NaCl should be produced when 9.20 g Na reacts with 14.2 g Cl_2?**

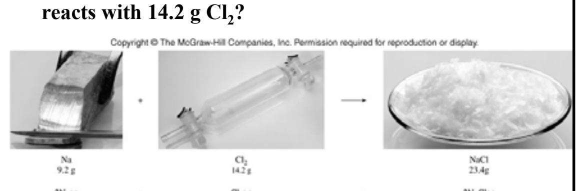


Figure 6.6

19

6.4 Limiting Reactants

- When two reactants are mixed, one usually does not react completely because there is too much of it.

In this reaction of sodium metal and greenish-yellow chlorine gas, one reactant is in excess in each case.

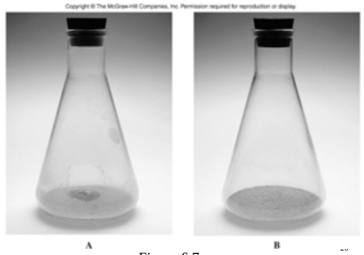


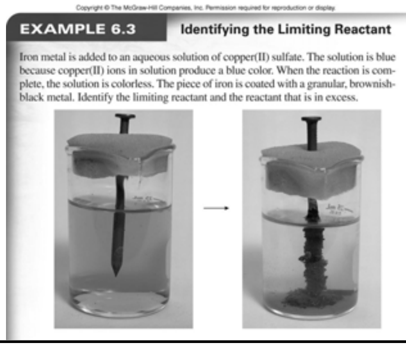
Figure 6.7

Limiting Reactant

- The limiting reactant is the reactant that reacts completely and is therefore not present when the reaction is complete.
- Since the limiting reactant reacts completely, its amount determines the amount of product that can form.

21

What is the limiting reactant? $Fe(s) + CuSO_4(aq) \rightarrow$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EXAMPLE 6.3 **Identifying the Limiting Reactant**

Iron metal is added to an aqueous solution of copper(II) sulfate. The solution is blue because copper(II) ions in solution produce a blue color. When the reaction is complete, the solution is colorless. The piece of iron is coated with a granular, brownish-black metal. Identify the limiting reactant and the reactant that is in excess.

22

Consider an Analogy:
The construction of a model solar car

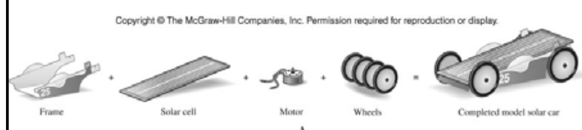
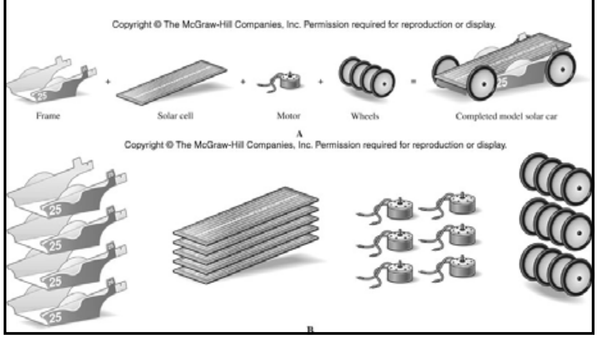


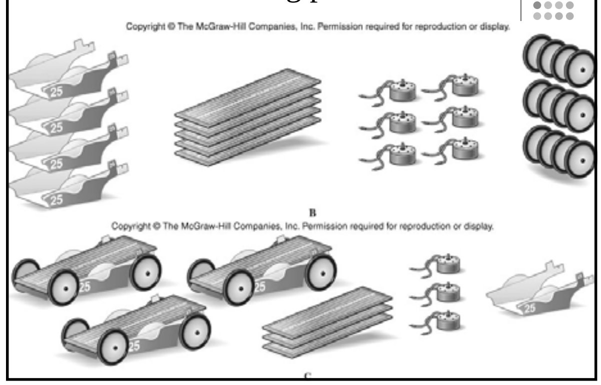
Figure 6.8

23

If you have 4 frames, 4 solar cells, 6 wheels, and 12 wheels, how many solar cars can you make?

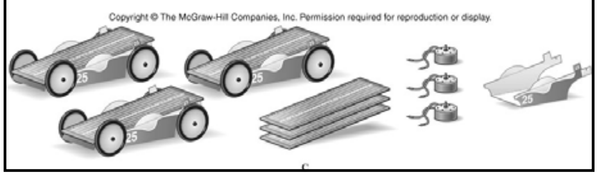


What is the limiting part?



What is the limiting part?

- **The wheel is the limiting part because it is completely used up.**
- **The number of cars made is dependent upon the number of wheels available. If there were 4 more wheels, then another car could have been made with the remaining parts.**



Limiting Reactants at a Molecular Level

- **In a chemical reaction, the balanced equation tells us the relative number of molecules (or moles) that combine in the reaction.**

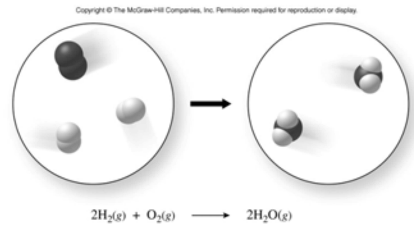


Figure 6.9

27

Limiting Reactants at a Molecular Level

- **If reactants are not present in this ratio, then there will be a limiting reactant and excess of the other reactant.**

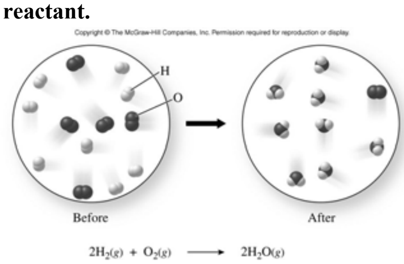
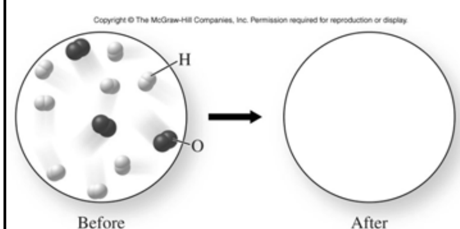


Figure 6.10

28

$2H_2(g) + O_2(g) \rightarrow 2H_2O(g)$

- Complete the after picture. How many H_2O molecules form?
- What is the limiting reactant? What is in excess?

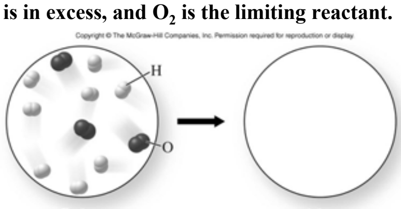


Limit_React

29

$2H_2(g) + O_2(g) \rightarrow 2H_2O(g)$

- **You can also use "molecule" ratios to determine the limiting reactant.**
- **The 8 H_2 molecules need 4 O_2 molecules to react with them.**
- **There are only 3 O_2 molecules, so all the H_2 cannot react.**
- **H_2 is in excess, and O_2 is the limiting reactant.**



30

Limiting Reactants – Mole Scale

- **$N_2(g) + 3H_2(g) \rightarrow 2NH_3(g)$**

1. **Identify the limiting reactant when the following are mixed:**
   a) **2.0 mol N_2 and 5.0 mole H_2**
   b) **3.10 mole N_2 and 10.2 mol H_2**
2. **How many moles of NH_3 can be produced in each case?**

31

6.5 Percent Yield

- The amount of product actually obtained in the lab (actual yield) is usually less than the amount predicted by calculations (theoretical yield).
- Yields describe the amount of product, and can be in mass units, moles, or number of molecules.

Figure 6.11

32

Percent Yield

- The percent yield describes how much of a product is actually obtained relative to the amount that should form assuming complete reaction of the limiting reactant.

$$\text{Percent Yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100$$

33

Percent Yield

- $2Na(s) + Cl_2(g) \rightarrow 2NaCl(s)$
- If 0.20 mol chlorine reacts with excess sodium, and 0.40 mol NaCl are produced, what is the percent yield for the reaction?

$$\text{Percent Yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100$$

34

Percent Yield

- $2Na(s) + Cl_2(g) \rightarrow 2NaCl(s)$
- If 0.450 mol chlorine reacts with excess sodium, and 0.385 mol NaCl are produced, what is the percent yield for the reaction?

$$\text{Percent Yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100$$

35

6.6 Energy Changes

- When methane reacts with oxygen when you use a gas stove, it's obvious that an energy change is occurring. Heat is released to the surroundings and is used to heat water and cook food.
- All chemical and physical changes are accompanied by energy changes.

36

Law of Conservation of Energy

- When energy is released from the atoms of a chemical reaction, it is transferred to the surroundings. The amount released by the reaction is equal to the amount absorbed by the surroundings.
- Energy can also be converted from one type to another.

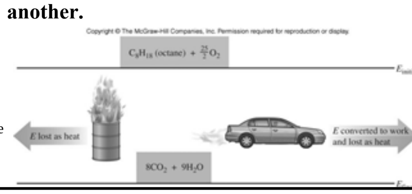


Figure 6.12

In an ICE, 32% of the energy is converted to work.

37

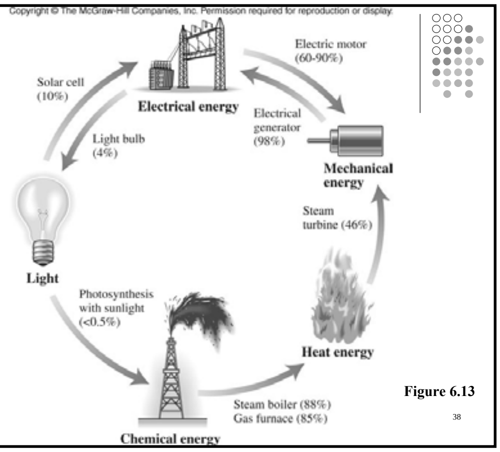


Figure 6.13

38

Efficiency

- No conversion is totally efficient – some amount of energy is always lost to the surrounding as heat.

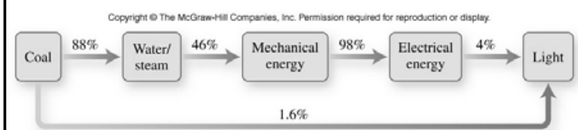


Figure 6.14

39

Energy Changes that Accompany Chemical Reactions

- Is energy absorbed or released by the reaction in each case? What happens to the temperature of the surroundings?

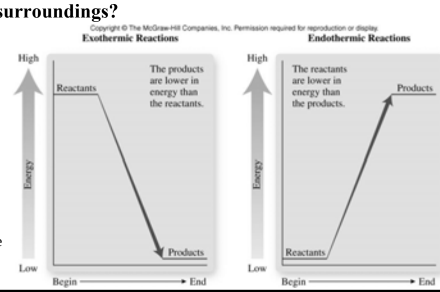
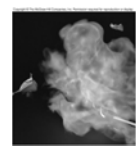


Figure 6.15

40

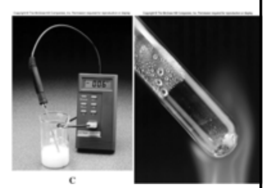
Endothermic and Exothermic Reactions

- Most chemical reactions are exothermic – they release energy to the surroundings.
  - e.g. $2H_2(g) + O_2(g) \rightarrow 2H_2O(g)$



exo

- Some reactions are endothermic, absorbing energy from the surroundings and cooling them.



endo

Quantities of Heat

- In chemistry, quantities of energy (and heat) are usually expressed with units of joules (J) or calories (cal).
- 1 cal = 4.184 J
- Nutritionists us the Calorie (Cal) which is a kilocalorie (kcal), or 1000 cal.

Specific Heat

- When heat is added to a substance, the substance increases in temperature.
- The amount of heat required to increase the temperature of 1 gram of a substance is dependent upon the identity of that substance, and is called the specific heat of that substance.
- Specific heat units: J/(g °C) or cal/(g °C)
- The specific heat of water is 4.184 J/(g °C).

43

TABLE 6.2 Specific Heats of Some Substances

Substance	Specific Heat J/(g °C)	Specific Heat cal/(g °C)	Substance	Specific Heat J/(g °C)	Specific Heat cal/(g °C)
Aluminum (*s*)	0.895	0.214	Water (*s*)	2.027	0.484
Carbon (diamond)	0.508	0.121	Water (*l*)	4.184	1.000
Carbon (graphite)	0.708	0.169	Water (*g*)	2.015	0.482
Calcium (*s*)	0.656	0.157	Asphalt	0.920	0.220
Chromium (*s*)	0.450	0.108	Bone	0.440	0.105
Copper (*s*)	0.377	0.0900	Brick	0.84	0.20
Gold (*s*)	0.129	0.0310	Cheddar cheese	2.60	0.621
Iodine (*s*)	0.214	0.0510	Concrete	0.88	0.21
Iron (*s*)	0.448	0.107	Glass	0.84	0.20
Lead (*s*)	0.129	0.0310	Granite	0.79	0.19
Mercury (*l*)	0.140	0.0335	Marble	0.86	0.21
Silver (*s*)	0.234	0.0560	Olive oil	1.79	0.428
Tin (*s*)	0.222	0.0530	Sand	0.835	0.200
Uranium (*s*)	0.117	0.0280	Strawberries	3.89	0.930
			Wax	2.89	0.69

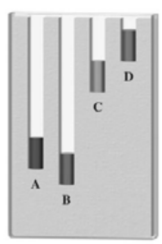
Specific Heat

- **How much heat is required to increase the temperature of 1 g of water by 10°C?**
- **How much heat is required to increase the temperature of 100 g of water by 1°C?**

45

EXAMPLE 6.10 Factors Affecting Heat

Samples of different metals having the same mass are heated to the same temperature and are then allowed to cool in wax. When all have cooled to the same temperature, they have melted through different amounts of the wax. Which of the metals has the greatest specific heat?



Specific Heat

- **heat = mass × specific heat × temperature change**
- $q = m \times C \times \Delta T$
- **How much heat must be added to 15.0 g of water to increase its temperature from 25.0 to 75.0°C?**
- **What is the heat change when 15.0 grams of water cools from 75.0 to 25.0°C?**

47

Meaning of the Sign of *q*

$$q_{\text{system}} + q_{\text{surroundings}} = 0$$

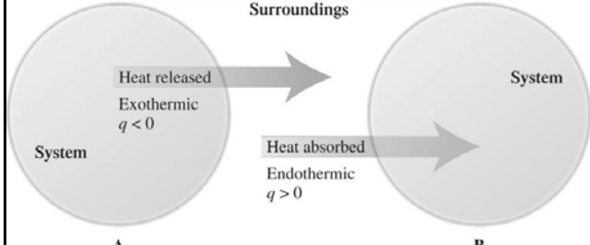


Figure 6.16

Specific Heat

- **If 1 kJ of heat were added to each of the following 50.0-gram substances, which would increase in temperature by the greatest amount?**
  - **Aluminum: 0.895 J/(g °C)**
  - **Copper: 0.377 J/(g °C)**
  - **Lead: 0.129 J/(g °C)**

49

Calorimetry

- Calorimetry is used to determine the heat change of a system by measuring the heat change of its surroundings.
- In this calorimeter, an insulated cup is used so the surroundings is limited to what is inside the cup.

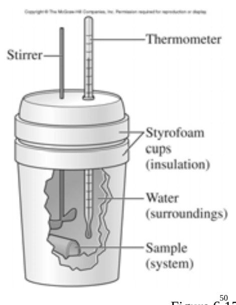


Figure 6.17

50

Calorimetry

- A 92.0-g piece of copper pipe is heated and then placed into this calorimeter with 100.0 g of water at 25.00°C. The final temperature of the mixture is 29.45°C.
- What is the heat change (q) of the pipe?

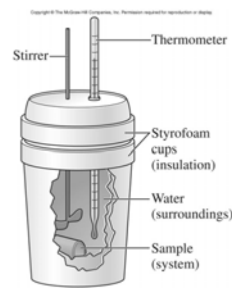
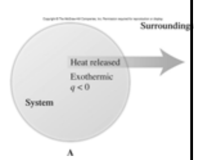


Figure 6.17

Calorimetry

- $q = m \times C \times \Delta T$
- q_{water} = 100.0 g × 4.184 J/(g°C) × (29.45–25.00 °C)
- q_{water} = 1860 J
- $q_{pipe} + q_{water} = 0$
- $q_{pipe} = -\,q_{water}$
- q_{pipe} = – (1860 J)
- q_{pipe} = – 1860 J
  - **The copper pipe released 1860 J to the surroundings**



52

Quantities of Heat Changes that Accompany Chemical Reactions

- The heat change for a chemical reaction can be determined in the same way as the heat change for the piece of copper pipe, if the reaction takes place in solution.

$$q_{reaction} + q_{surroundings} = 0$$

- If the reaction does not take place in solution, such as a combustion reaction, then a bomb calorimeter is required.

53

System and Surroundings

Bomb Calorimeter (For Non-Aqueous Reactions)

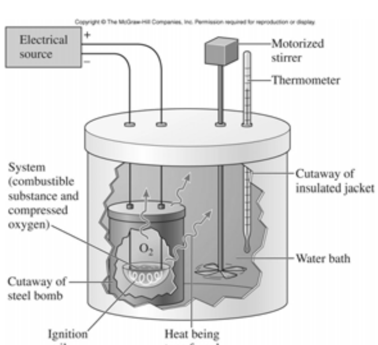
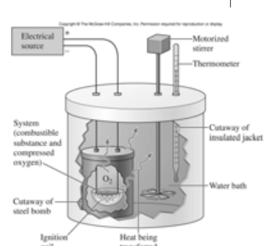


Figure 6.18

54

Bomb Calorimeter (For Non-Aqueous Reactions)

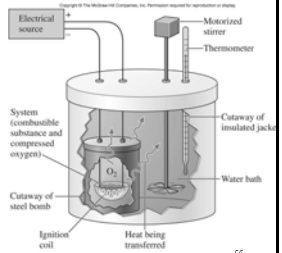
- **When an exothermic reaction takes place, the water in the calorimeter absorbs the heat from the reaction and increases in temperature.**
- $q_{rxn} = -\,q_{calorimeter}$



55

Bomb Calorimeter
(For Non-Aqueous Reactions)

- When 5.0 grams of methanol is burned in a calorimeter, the temperature of the calorimeter increases from 20.0 to 35.0°C. The heat capacity of the calorimeter is 7.70 kJ/ °C.
  - What is the heat of combustion per gram of methanol?



56

TABLE 6.3 Heat Changes for the Combustion of Fuels
Substance + $xO_2(g) \longrightarrow yCO_2(g) + zH_2O(l)$

Fuel	Formula	Heat Change kJ/mol	Heat Change kJ/g
Hydrogen	$H_2(g)$	–286	–143
Methanol	$CH_3OH(l)$	–726	–23
Methane	$CH_4(g)$	–891	–56
Ethanol	$CH_3CH_2OH(l)$	–1367	–30
Acetylene	$C_2H_2(g)$	–1301	–50
Ethylene	$C_2H_4(g)$	–1411	–50
Ethane	$C_2H_6(g)$	–1561	–52
Propane	$C_3H_8(g)$	–2219	–50
Butane	$C_4H_{10}(l)$	–2878	–50
Octane	$C_8H_{18}(l)$	–5471	–48
Wood	—	—	–15
TNT	$C_7H_5(NO_2)_3(s)$	–3434	–15

Combustion of H_2

- The heat of combustion of H_2 is -286 kJ/mol. How much heat is released when a 1.2 L balloon filled with H_2 is burned?
  - Under normal conditions, each liter of a gas contains 0.040 mol of that gas.

58

Energy Content of Foods
as presented in most nutritional labels

TABLE 6.4 Energy Values of Food Components

Food Component	kcal/g (Cal/g)	kJ/g
Proteins	4	17
Fats	9	38
Carbohydrates	4	17