14.2 Thermochemical Equations

Section Preview/ Specific Expectations

In this section, you will

- **write** thermochemical equations
- **relate** bond breaking and bond making to endothermic and exothermic energy changes
- **communicate** your understanding of the following terms: *exothermic*, *thermochemical equation*, *endothermic*, *bond energy*

In the last section, you learned about acetylene, an important fuel in our society (Figure 14.6). You balanced the equation for the complete combustion of acetylene. You then produced acetylene in an investigation. What you did not consider, however, was the most useful product that our society gets from acetylene: heat energy. How can you represent the heat that is released during combustion as part of a chemical equation?

For now, you will use the word "energy" to represent the heat in an equation. In the next section, you will calculate numerical values for this energy and use these energy values in chemical equations.

In previous science courses, you studied reactions that involve a change in energy. Figure 14.7 reviews some important terms.

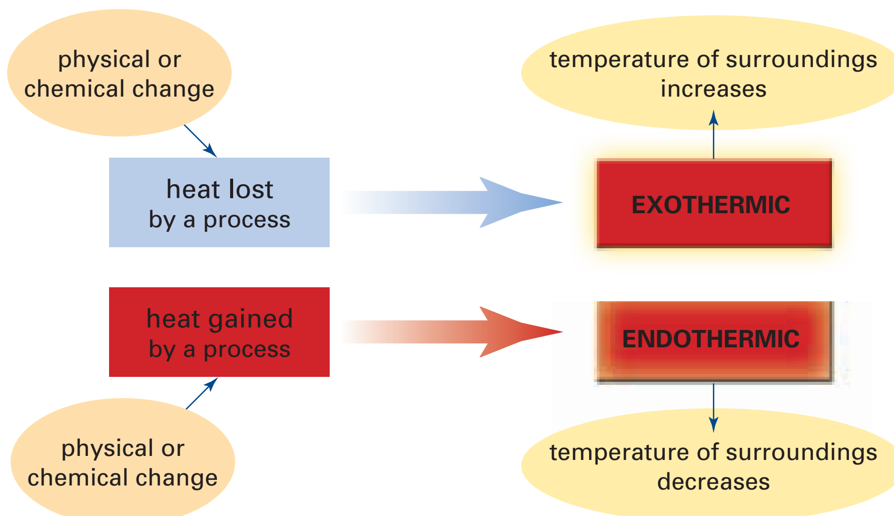


Figure 14.7

An **exothermic** reaction gives off heat. Combustion reactions are exothermic reactions because they produce heat. *Since the energy is a product of the reaction, it is shown on the product side of the equation.*

The combustion of acetylene is a good example of an exothermic reaction:

$$2C_2H_{2(g)} + 5O_{2(g)} \rightarrow 4CO_{2(g)} + 2H_2O_{(g)} + \text{energy}$$

When the energy is written as part of the chemical equation, the equation is called a **thermochemical equation**.

An **endothermic** reaction absorbs heat energy. Energy must be added to the reactants for an endothermic reaction to occur. *Since the energy is needed as a reactant, it is shown on the reactant side of the equation.*

Have you ever noticed that perfume or rubbing alcohol feels cool on your skin as it evaporates? The physical process of evaporation is endothermic. Energy is taken away from the surface of your skin, so you feel cool. The energy is added to the liquid alcohol or perfume solvent to make it a gas. The following equation shows the endothermic evaporation of isopropanol (a type of rubbing alcohol) from a liquid to a gas:

$$\text{energy} + CH_3CHOHCH_{3(\ell)} \rightarrow CH_3CHOHCH_{3(g)}$$

How can you tell that this process is not a chemical reaction?

Figure 14.6 The combustion of acetylene (ethyne) in an oxyacetylene torch produces the highest temperature (about 3300°C) of any known mixture of combustible gases. Metal workers can use the heat from this combustion to cut through most metal alloys.

Bond Breaking and Bond Making

The formation of acetylene (ethyne) gas from its elements is an endothermic reaction. The combustion of acetylene, however, is exothermic. In fact, it releases enough heat energy to cut steel! How can you explain the formation and combustion of acetylene in terms of bonds being broken and made? The answer to this question is fundamental to your understanding of the energy changes that occur in chemical reactions.

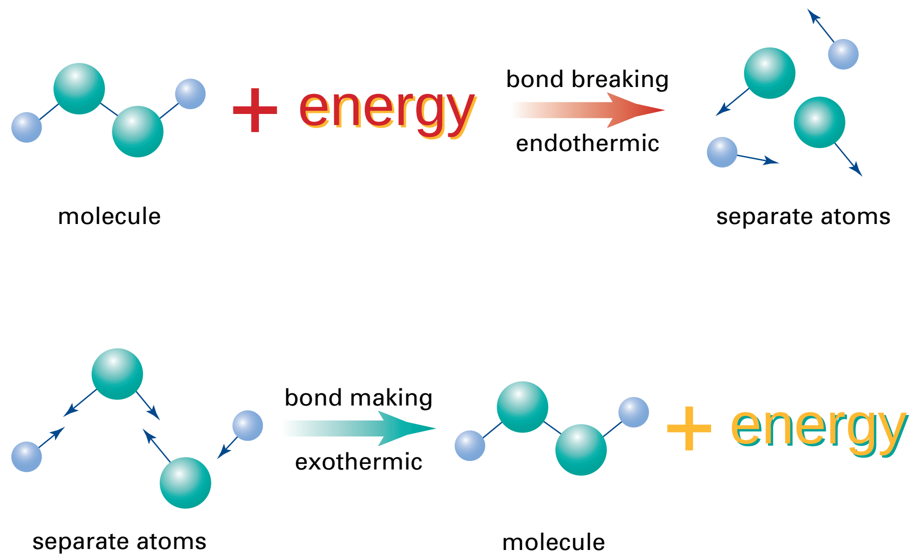


Figure 14.8 **This illustration shows bonds being broken and made during a chemical reaction. If the bonds are strong, there is a large change in energy. If the bonds are weak, there is a small change in energy.**

A chemical bond is caused by the attraction between the electrons and nuclei of two atoms. Energy is needed to break a chemical bond, just like energy is needed to break a link in a chain. On the other hand, making a chemical bond releases energy. The strength of a bond depends on how much energy is needed to break the bond. (see Figure 14.8.)

A specific amount of energy is needed to break each type of bond. When the same type of bond is formed, the same specific amount of energy is released. The energy that is absorbed or released when breaking or making a bond is called the **bond energy**. Bond energy is usually measured in kilojoules (kJ). Table 14.1 shows some average bond energies.

From the table, you can see that 347 kJ of energy is needed to break one mole of C—C bonds in a sample of propane or any other carbon. Similarly, 347 kJ of energy is released if one mole of C—C bonds forms in a sample of butane.

Every chemical reaction involves both bond breaking (reactant bonds are broken) *and* bond making (product bonds are formed). Since there are different types of bonds inside the reactant and product molecules, the bond breaking and bond making energies are different. This results in a net amount of energy for each reaction.

The next sample problem compares bond breaking and bond making in a combustion reaction.

mind STRETCH

(a) Use a molecular model kit to model the formation of butane from its elements: $4C_{(s)} + 5H_{2(g)} \rightarrow C_4H_{10(g)}$ Compare the bonds you break with the bonds you form.

(b) Using Table 14.1, estimate the energy needed to break the bonds of 5 mol of hydrogen gas. Compare this energy with the energy produced by making the bonds of 1 mol of butane gas. Predict whether the formation of butane is exothermic or endothermic.

(c) Look up "heat of formation" in a reference book such as *The CRC Handbook of Chemistry and Physics* to find the actual energy of this reaction. Is it exothermic (negative) or endothermic (positive)?

Note: Since bond energies are only a way of *estimating* the energy produced by the formation of a compound, your answer will not agree with the recognized value. Look at the Thinking Critically question in the Section Review to find out how to estimate the energy of a formation reaction more accurately.

Table 14.1 Average Bond Energies

Type of bond	Average energy (kJ/mol)
H—H	432
C—C	347
C=C	614
C≡C	839
C—H	413
C—O	358
C=O	745
O—H	467
O=O (in O_2)	498

Sample Problem

The Combustion of Acetylene

Problem

Consider bond breaking and bond making to explain why the combustion of acetylene is exothermic. Then write a thermochemical equation for the reaction, using the following balanced equation:

$$2C_2H_{2(g)} + 5O_{2(g)} \rightarrow 4CO_{2(g)} + 2H_2O_{(g)}$$

What Is Required?

You need to describe what happens when the reactant bonds are broken and what happens when the product bonds are formed. You need to compare the energy that is absorbed when the reactant bonds are broken with the energy that is released when the product bonds are formed. Then you need to write a thermochemical equation, using the word "energy."

What Is Given?

You know that energy is absorbed when bonds are broken and energy is released when bonds are formed. You also know that the equation is exothermic. (Overall, energy is released in this reaction.)

Plan Your Strategy

Step 1 Describe what happens when the reactant bonds are broken.

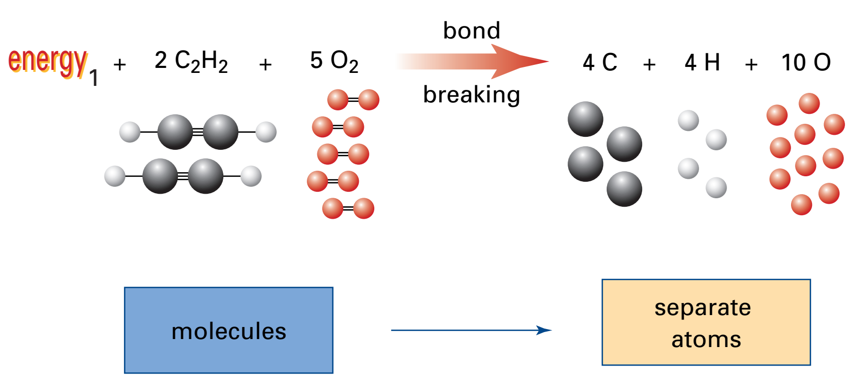
Step 2 Describe what happens when the product bonds are formed.

Step 3 Compare the energy that is absorbed when the reactant bonds are broken with the energy that is released when the product bonds are formed.

Step 4 Write the thermochemical equation, using the word "energy."

Act on Your Strategy

Step 1 The reactant bonds are broken. This process absorbs enough energy to split the reactants into separate atoms.



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PROBLEM TIP

- If the energy that is needed to break the reactant bonds is greater than the energy that is released when the product bonds form, the reaction is endothermic.
- If the energy that is needed to break the reactant bonds is less than the energy that is released when the product bonds form, the reaction is exothermic.
- If the reaction is endothermic, the energy is on the left side of the equation.
- If the reaction is exothermic, the energy is on the right side of the equation.

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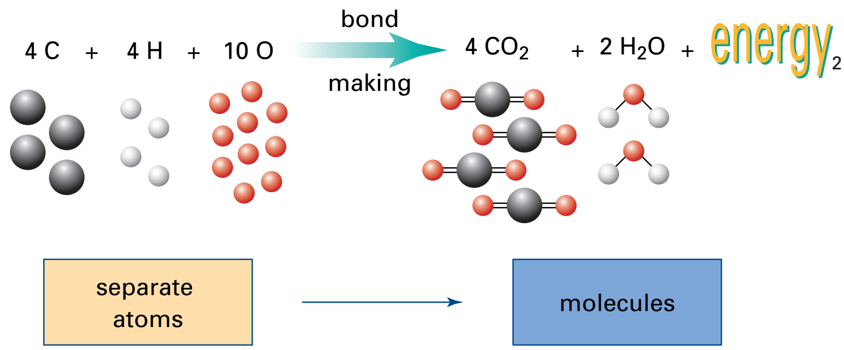
Step 2 The product bonds are made. This process releases energy as the product molecules are formed.



Step 3 The combustion of acetylene is exothermic. Therefore, the energy that is used when the reactant bonds are broken must be less than the energy that is released when the product bonds are formed.

$$\text{energy}_1 < \text{energy}_2$$

Step 4 The thermochemical equation is

$$2C_2H_{2(g)} + 5O_{2(g)} \rightarrow 4CO_{2(g)} + 2H_2O_{(g)} + \text{energy}$$

Check Your Solution

The equation is exothermic, so the energy is on the product side of the equation.

Practice Problems

6. The formation of propane from its elements is an exothermic reaction. The combustion of propane is also exothermic.
   - **(a)** Write the balanced thermochemical equation for the formation of propane.
   - **(b)** Write the balanced thermochemical equation for the combustion of propane. (The balanced equation is on page 580.)
   - **(c)** Consider the combustion of propane. Compare the energies of bond breaking and bond making to explain why the reaction is exothermic.
7. **(a)** Explain why the formation of ethene, $C_2H_{4(g)}$, from its elements is endothermic, while its combustion is exothermic.
   - **(b)** Write the balanced thermochemical equations for the formation and the combustion of ethene.

PROBLEM TIP

Remember that different types of bonds have different bond energies. The bonds that are broken in the reactants are different from the bonds that are formed in the products. The net energy for the entire reaction is the difference between energy_1 and energy_2.

So far, you have been using the word "energy" in thermochemical equations to represent the net energy. It is preferable to have a numerical value for the amount of energy when talking about endothermic and exothermic processes. In the next section, you will see how the net energy in a process can be measured. You will even measure some energy values yourself!

Section Review

1 K/U Choose the correct term in each box to describe the given thermochemical equation. Name the organic compounds.

(a)

$$\text{energy} + 2C_{(s)} + H_{2(g)} \xrightarrow[\boxed{\text{net energy is absorbed/released}}]{\boxed{\text{endothermic/exothermic}}} C_2H_{2(g)}$$

(b)

$$CH_{4(g)} + 2O_{2(g)} \xrightarrow[\boxed{\text{net energy is absorbed/released}}]{\boxed{\text{endothermic/exothermic}}} CO_{2(g)} + 2H_2O_{(g)} + \text{energy}$$

2 K/U If an overall reaction is endothermic, which process involves more energy: breaking the reactant bonds or making the product bonds?

3 **(a)** C When energy is absorbed in a reaction to break the bonds in the reactants, where does the energy go?

(b) C When energy is released to form the bonds in the products, where does the energy go?

4 MC Flour, sugar, eggs, and milk are combined and baked to produce cookies.

(a) Is this reaction exothermic or endothermic? Explain.

(b) Write a word equation that includes the word "energy" to describe this reaction.

5 K/U In the MindStretch on page 589, you used bond energies to estimate the energy of a reaction. Your estimated value was very different from the actual value, however. This is because solid carbon must become gaseous *before* reacting to form a hydrocarbon. The change of state takes additional energy.

$$C_{(s)} + 715\text{ kJ} \rightarrow C_{(g)}$$

Use the information above, along with the bond energies in Table 14.1, to estimate the energy needed to form acetylene, $C_2H_{2(g)}$, from its elements.

$$2C_{(s)} + H_{2(g)} \rightarrow C_2H_{2(g)}$$

Remember to consider the breaking of the H—H bonds, and the forming of the C—H and C≡C bonds. Compare your answer with the recognized value, 226.7 kJ/mol.