SECTION 3.3

Combustion Reactions

In some areas of the Arctic, large amounts of methane, $CH_4(g)$, are entering the atmosphere. As the climate becomes warmer and the ground thaws, bacteria produce methane from the remains of dead plants and animals. The release of large amounts of methane into the atmosphere is a concern because methane is an important greenhouse gas that contributes to global warming. Molecule for molecule, methane has 25 times the warming effect that carbon dioxide has. **Figure 3.20** shows how researchers ignite gas bubbles that are released from the ground and from lakes to test whether they contain methane. As the methane burns, it undergoes chemical changes and new substances form. The reaction that is taking place is known as a combustion reaction.

Key Terms

combustion reaction
hydrocarbon
soot

Figure 3.20 University of Alaska Fairbanks researcher Katey Walter lights a pocket of methane on a thermokarst lake in Siberia in March of 2007. Igniting the gas is a way to demonstrate, in the field, that it contains methane.

Characteristics of Combustion Reactions with Hydrocarbons

In a **combustion reaction**, like the one shown in **Figure 3.20**, oxygen combines with another substance and releases energy in the form of heat and light. One or more oxides, compounds that are composed of oxygen, are produced. For example, the combustion of methane, modelled in **Figure 3.21**, produces the oxides carbon dioxide and water (dihydrogen monoxide). Methane is a **hydrocarbon**, a compound that is composed only of the elements carbon and hydrogen. The combustion of hydrocarbons can be either complete or incomplete, as you will learn in this section.

combustion reaction the reaction of a substance with oxygen, producing one or more oxides, heat, and light

hydrocarbon a compound that is composed only of the elements carbon and hydrogen

$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g)$$

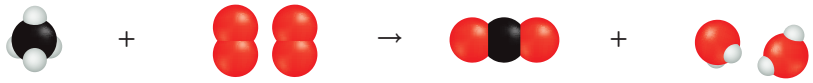


Figure 3.21 Oxygen is always a reactant in a combustion reaction, such as the complete combustion of methane, which is modelled here.

Combustion reactions can occur with other substances, such as fluorine, that can react in a similar way as oxygen does. You will learn more about these types of combustion reactions in Grade 12.

Complete Combustion of Hydrocarbons

Like many of the other hydrocarbons shown in **Table 3.4**, methane is a fuel.

Table 3.4 Hydrocarbons and Their Uses

Name	Formula	Use
methane	$CH_4(g)$	Fuel used for heating and cooking
ethane	$C_2H_6(g)$	Raw material used for making plastics
propane	$C_3H_8(g)$	Fuel used for heating and cooking
butane	$C_4H_{10}(g)$	Fuel used in lighters; propellant
acetylene (ethyne)	$C_2H_2(g)$	Fuel used for welding
benzene	$C_6H_6(\ell)$	Substance used in the manufacture of paints, plastics, and detergents

These hydrocarbons, as well as many others, can undergo combustion reactions to produce carbon dioxide and water. When a hydrocarbon burns, the products of the reaction depend on the amount of oxygen that is present. When oxygen is available in sufficient amounts, complete combustion occurs. All the carbon atoms and hydrogen atoms from the hydrocarbon molecules combine with oxygen atoms to form molecules of the oxides carbon dioxide and water vapour. The general form of the complete combustion of a hydrocarbon is

$$\begin{array}{ccccccc} \text{hydrocarbon} & + & \text{oxygen} & \rightarrow & \text{carbon dioxide} & + & \text{water} \\ C_xH_y & + & O_2(g) & \rightarrow & CO_2(g) & + & H_2O(g) \end{array}$$

Welding, shown in **Figure 3.22**, is an example of a process that depends on hydrocarbon combustion.

Figure 3.23 A blue flame indicates that complete combustion is occurring.

Figure 3.22 This welding torch uses acetylene, a hydrocarbon, as fuel.

The colour of the flame in a combustion reaction can indicate whether complete combustion is occurring. Natural gas, which is mainly composed of methane, is used in many homes for heating and cooking. It is also used in laboratory burners, such as the one in **Figure 3.23**.When using a gas laboratory burner, it is important to adjust the air vents to allow the proper amount of oxygen to enter the burner. If the flame is yellow, more oxygen is needed for complete combustion to occur. The blue flame that forms during complete combustion generates mostly heat and very little light. In other words, complete combustion is a more efficient process for generating heat.

Incomplete Combustion of Hydrocarbons

As you have learned, having the correct amount of oxygen results in complete combustion and having too little oxygen results in incomplete combustion. Incomplete combustion is sometimes useful because it produces a bright yellow flame, such as the candle flame in **Figure 3.24**. However, it can also be a hazard. In addition to producing carbon dioxide and water vapour, an incomplete combustion reaction can produce elemental carbon, or **soot**, and toxic carbon monoxide, CO(g). For example, the incomplete combustion of propane, $C_3H_8(g)$, can occur according to this chemical equation:

soot fine particles consisting mostly of carbon, formed during the incomplete combustion of a hydrocarbon

propane + oxygen → carbon + carbon monoxide + carbon dioxide + water

$$2C_3H_8(g) + 7O_2(g) \rightarrow 2C(s) + 2CO(g) + 2CO_2(g) + 8H_2O(g)$$

In addition, the incomplete combustion of propane can result in many other ratios of carbon products.

Figure 3.24 The yellow flame of this candle indicates that incomplete combustion is occurring. The colour of the candle flame is produced by carbon particles within it that are hot enough to glow.

***Identify** the product in this combustion reaction that can cause deposits of a dark substance to form on nearby surfaces.*

Suggested Investigation

Plan Your Own Investigation 3-B, Comparing Complete and Incomplete Combustion

The production of carbon monoxide is a serious concern when incomplete combustion reactions are taking place. Carbon monoxide is a toxic gas with no colour or odour. Its molecules are similar in size and shape to diatomic oxygen molecules. This similarity allows carbon monoxide to bind to oxygen binding sites in the blood more tightly than oxygen itself. The longer a person inhales carbon monoxide, the fewer binding sites that are available to carry oxygen. Initial symptoms of carbon monoxide poisoning include headache, dizziness, or nausea. Prolonged or high exposure can result in vomiting, collapse, loss of consciousness, and eventually suffocation.

Carbon monoxide can build up to harmful levels in some industries, such as pulp and paper production, petroleum refineries, and steel production. Taxi drivers, welders, forklift operators, and other people who work in enclosed spaces where combustion reactions occur are at risk. Proper ventilation and a procedure for reporting signs of possible exposure are key to avoiding carbon monoxide poisoning. In addition, carbon monoxide detectors are important for monitoring the level of this deadly gas.

The Sample Problems on the next two pages show chemical equations for complete combustion reactions and incomplete combustion reactions. You can practise balancing these types of equations in the Practice Problems that follow.

Learning Check

19. What types of energy do combustion reactions release?

20. What is a hydrocarbon?

- **a.** In what kinds of combustion reactions can hydrocarbons take part?
- **b.** What are the products of a complete combustion reaction involving a hydrocarbon and oxygen?

21. During the reaction of nitrogen gas and oxygen gas to form nitrous oxide gas, $N_2O(g)$, energy in the form of heat is absorbed.

- **a.** Is this reaction a combustion reaction? Explain your reasoning.
- **b.** If you concluded that this reaction is not a combustion reaction, identify which type of reaction it is.

22. Compare **Figure 3.23** and **Figure 3.24**.

- **a.** In terms of the type of combustion reaction occurring, explain why the flames in the two figures are different colours.
- **b.** Explain whether the flame shown in **Figure 3.23** is generating more heat or more light.
- **c.** List the products that are being formed by the combustion reaction shown in each figure.

23. Do you expect a gas stove to be designed so that complete combustion occurs? Explain your reasoning.

24. A science fiction movie shows a scene on the outside of a spaceship in outer space. In the scene, a stray shot from a blaster ignites an antenna array, which begins to burn. Analyze the scientific accuracy of this scene based on your understanding of combustion reactions.

Sample Problem A

Writing Balanced Chemical Equations for Complete Combustion Reactions

Problem

What is the balanced chemical equation for the complete combustion of butane, $C_4H_{10}(g)$?

What Is Required?

A balanced chemical equation for the complete combustion of butane is required.

What Is Given?

You are given the reactant: butane.
You are given the type of reaction: complete combustion.

Plan Your Strategy	Act on Your Strategy
Identify the reactants. Butane is one of the reactants. Because the reaction is a combustion reaction, the other reactant must be oxygen.	Reactants: $C_4H_{10}(g)$, $O_2(g)$
Identify the products. Because the reaction is a complete combustion reaction, the products must be carbon dioxide and water.	Products: $CO_2(g)$, $H_2O(g)$
Write a balanced chemical equation for the reaction.	$2C_4H_{10}(g) + 13O_2(g) \rightarrow 8CO_2(g) + 10H_2O(g)$

Check Your Solution

The chemical formula for each substance is written correctly. The number of atoms of each element is equal on both sides of the equation. The coefficients are written in the lowest possible ratio.

Sample Problem B

Writing Balanced Chemical Equations for Incomplete Combustion Reactions

Problem

Write a balanced chemical equation for the incomplete combustion of hexane, $C_6H_{14}(\ell)$, given the following partial chemical equation:

$C_6H_{14}(\ell) + 5O_2(g) \rightarrow CO_2(g) + CO(g) + \_\_\_\_ + \_\_\_\_ H_2O(g)$

What Is Required?

A balanced chemical equation for the incomplete combustion of hexane is required, based on the given partial chemical equation.

What Is Given?

You are given a partial chemical equation:

$C_6H_{14}(\ell) + 5O_2(g) \rightarrow CO_2(g) + CO(g) + \_\_\_\_ + \_\_\_\_ H_2O(g)$

You know the type of reaction: incomplete combustion.

Plan Your Strategy	Act on Your Strategy
Identify the reactants. Because there is insufficient oxygen present for complete combustion to occur, the coefficient for oxygen is provided in the question.	Reactants: $C_6H_{14}(\ell)$, $5O_2(g)$
Identify the possible products. The products of an incomplete combustion reaction may include either elemental carbon or carbon monoxide gas, or both.	Possible products: $CO_2(g)$, $H_2O(g)$, $C(s)$, $CO(g)$
Examine the partial chemical equation, and identify the missing information. One product is not given, and the coefficient for $H_2O(g)$ is not given. Begin balancing the equation with the information you have. Identify the missing product.	$C_6H_{14}(\ell) + 5O_2(g) \rightarrow CO_2(g) + CO(g) + \_\_\_\_ + 7H_2O(g)$ The numbers of hydrogen atoms and oxygen atoms are equal on both sides of the equation, but there are more carbon atoms in the reactants than in the products. The missing product must be elemental carbon.
Write the balanced chemical equation for the incomplete combustion reaction.	$C_6H_{14}(\ell) + 5O_2(g) \rightarrow CO_2(g) + CO(g) + 4C(s) + 7H_2O(g)$

Check Your Solution

The chemical formula for each substance is written correctly. The number of atoms of each element is equal on both sides of the equation. The coefficients are written in the lowest possible ratio.

Practice Problems

Write a balanced chemical equation for each chemical reaction.

41. complete combustion of heptane, $C_7H_{16}(\ell)$

42. complete combustion of nonane, $C_9H_{20}(\ell)$

43. complete combustion of acetylene, $C_2H_2(g)$

44. complete combustion of benzene, $C_6H_6(\ell)$

45. complete combustion of octane, $C_8H_{18}(\ell)$

46. incomplete combustion of octane:
$2C_8H_{18}(\ell) + 17O_2(g) \rightarrow \_\_CO(g) + \_\_H_2O(g)$

47. incomplete combustion of pentane:
$2C_5H_{12}(\ell) + 11O_2(g) \rightarrow \_\_\_\_ + 12H_2O(g)$

48. incomplete combustion of propane:
$C_3H_8(g) + 2O_2(g) \rightarrow \_\_\_\_ + \_\_H_2O(g)$

49. incomplete combustion of heptane: $4C_7H_{16}(\ell) + 37O_2(g) \rightarrow \_\_CO_2(g) + \_\_CO(g) + \_\_H_2O(g)$

50. incomplete combustion of cyclohexane:

a. $C_6H_{12}(\ell) + 6O_2(g) \rightarrow \_\_\_\_ + 6H_2O(g)$

b. $C_6H_{12}(\ell) + 3O_2(g) \rightarrow \_\_\_\_ + 6H_2O(g)$

Characteristics of Combustion Reactions with Other Chemicals

In addition to hydrocarbons, many other substances can combine with oxygen in combustion reactions. For instance, when hydrogen is burned as a fuel for a spacecraft, such as the space shuttle, it undergoes a combustion reaction in which water is produced. This reaction is modelled in **Figure 3.25 (A)**. **Figure 3.25 (B)** shows a demonstration of the combustion of hydrogen. The combustion reaction between hydrogen and oxygen is also a synthesis reaction because multiple reactants combine to form a single product.

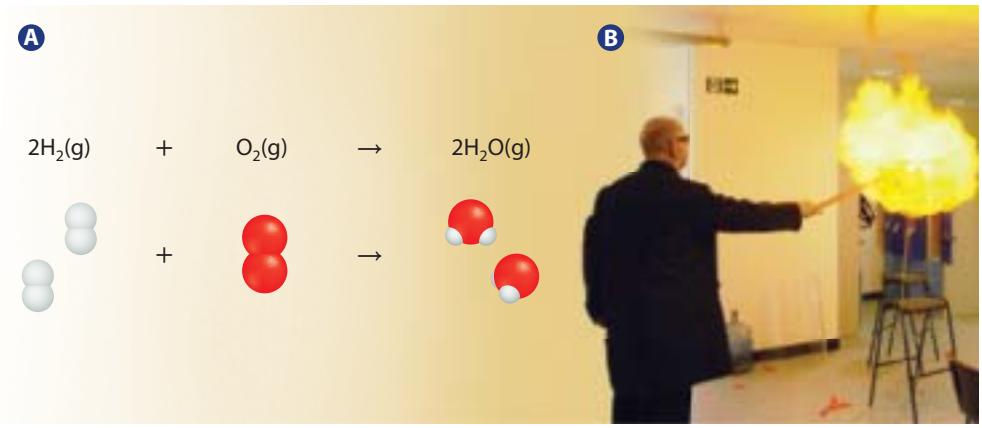


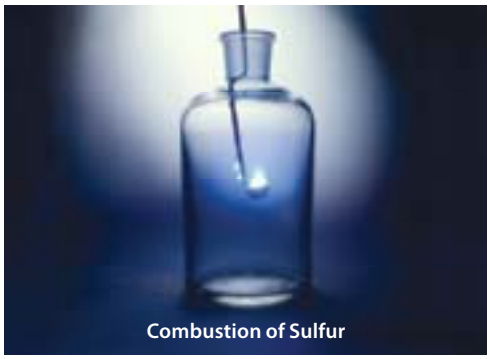
Figure 3.25 Hydrogen and oxygen react to form water during a combustion reaction **(A)**. A hydrogen-filled balloon is ignited in **(B)** to demonstrate the combustion of hydrogen.

Analyze *Why is this reaction classified as a combustion reaction?*

Suggested Investigation

Inquiry Investigation 3-C, Conducting Synthesis, Decomposition, and Combustion Reactions

You have also encountered combustion reactions involving other chemicals in your study of synthesis reactions. For example, the reaction of sulfur with oxygen, which is involved in the formation of acid precipitation, is both a combustion reaction and a synthesis reaction. Similarly, the reaction of magnesium with oxygen can be classified as both a synthesis reaction and a combustion reaction. In these reactions, energy in the form of heat and light is released, as shown in **Figure 3.26**.



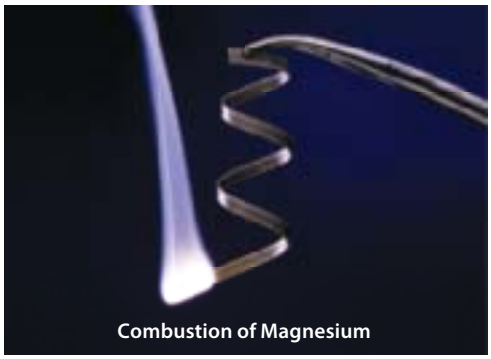


Figure 3.26 Each of these elements undergoes a combustion reaction with oxygen.

Compare *How are the products of these reactions similar?*

Combustion Reactions and Life Processes

So far, you have learned about combustion reactions mainly in industrial and atmospheric applications—applications that are non-living. For example, when glucose, a common form of sugar, is burned, it reacts with oxygen gas to produce carbon dioxide, water, and a large amount of energy. The combustion of glucose can be represented by the chemical equation below.

$$C_6H_{12}O_6(s) + 6O_2(g) \rightarrow 6CO_2(g) + 6H_2O(g)$$

However, this chemical equation also applies to reactions taking place in living cells that are necessary to sustain life.

Cellular Respiration

The equation for the combustion of glucose also summarizes a series of reactions that occur during a process called cellular respiration, which is the metabolism of glucose in living cells. Some of the energy that is released during cellular respiration is captured to fuel metabolic processes. The rest is released as heat. **Table 3.5** highlights some of the differences between combustion and cellular respiration.

Table 3.5 Comparison of Combustion and Cellular Respiration

Characteristics	Combustion	Cellular Respiration
Speed	Is a faster process	Is a slower process
Temperature	Generally occurs at high temperatures	Occurs at body temperatures
Complete or incomplete reaction	May be incomplete, producing soot and carbon monoxide	Always complete, producing carbon dioxide, water, and energy
Duration	Is not a continuous process	Occurs at all times within living cells

Learning Check

25. Describe incomplete combustion.

26. Why is incomplete combustion potentially hazardous?

27. List three industries in which carbon monoxide exposure can occur.

28. What determines whether complete or incomplete combustion will occur?

29. When can a synthesis reaction also be classified as a combustion reaction?

30. Bacteria that are involved in the decomposition of once-living material carry out the process represented by the following overall chemical equation:

glucose + oxygen $\longrightarrow$ carbon dioxide + water

Would you describe this process as combustion or cellular respiration? Explain your answer.

Summarizing Synthesis, Decomposition, and Combustion Reactions

In this chapter, you have learned about synthesis, decomposition, and combustion reactions. By identifying the type of reaction, you can better predict how the reactants will interact and what products will likely form. **Table 3.6** summarizes the key characteristics of each type of reaction discussed in this chapter. You can use **Table 3.6** to help you classify chemical reactions. In Chapter 4, you will learn about two more types of reactions. Keep in mind that all the types of reactions you will learn about in this course represent only a very small portion of known reactions.

Table 3.6 Characteristics of Synthesis, Decomposition, and Combustion Reactions

Type of Reaction	General Form	Key Characteristics
Synthesis reaction	$A + B \longrightarrow AB$	Two elements or small compounds combine to form a single product.
Decomposition reaction	$AB \longrightarrow A + B$	A single reactant breaks apart to form two or more products.
Combustion reaction	element or compound + $O_2(g) \longrightarrow$ oxides	Oxygen reacts with an element or compound to form one or more oxides. Energy, in the form of heat and light, is produced.

STSE FEATURE

QUIRKS & QUARKS

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THIS WEEK ON QUIRKS & QUARKS

Power, Sweet Power

You likely use batteries every day in devices such as watches, cellphones, and laptops.

Most batteries are made from metals and acids. They convert the chemical energy in an electrolyte into electrical energy that can do work. The electrolyte is usually an acid paste, and the electrodes commonly contain toxic metals, such as lead, cadmium, and mercury. Unfortunately, old or discarded batteries can break down and release these toxic substances into the environment.

Because of the potential hazards of batteries, some scientists are trying to develop other types of batteries, made from less toxic substances. Dr. Shelley Minteer from St. Louis University has developed a prototype of an electricity-producing fuel cell that runs on sugar. Bob McDonald interviewed Dr. Minteer to learn more.

A Natural Solution

Minteer saw that batteries are inefficient, and that the heavy metals they use pose environmental risks. By contrast, living cells use a very efficient system, in which a carbohydrate, glucose, goes through a series of reactions, collectively known as cellular respiration, to produce all the energy that is needed by the cells. Minteer wanted to mimic cellular respiration at an electrode surface.

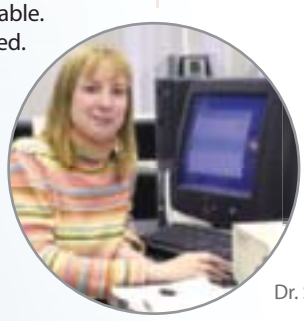
The sugar fuel cell Minteer developed uses a few millilitres of sugar water and two electrodes. Each electrode is about the size of a postage stamp and coated with enzymes like those found in living cells. The enzymes break down sucrose into simpler sugars, such as glucose, which react at the electrodes to produce carbon dioxide, water, and electrical energy.

Three or four times longer-lasting than a typical cellphone battery, the internal components of the sugar fuel cell are completely naturally sourced (the enzymes come from potatoes), and biodegradable. To recharge the fuel cell, sugar is added. The fuel cell uses no toxic metals or potentially dangerous chemicals, unlike most regular batteries and fuel cells. This technology may be well suited to small portable electronic devices that currently use rechargeable batteries.

Related Career

Electrochemists study the relationship between electricity and chemical changes, such as electrolysis, corrosion, and the chemical changes that occur in batteries. Electrochemists also study lightning, luminescence, and neurons.

Go to **scienceontario** to find out more



Dr. Shelley Minteer

When a fuel cell runs on sugar, its fuel is always close at hand. In the future, cellphones could possibly be powered by maple syrup or soft drinks!

QUESTIONS

1. The overall reaction that takes place in Dr. Minteer's sugar fuel cell is the same as the overall reaction for cellular respiration. In both cases, glucose, $C_6H_{12}O_6(aq)$, reacts with oxygen to form water and carbon dioxide. What is the chemical equation for cellular respiration, and how would you classify it?
2. How could Dr. Minteer's invention help to protect the environment?
3. Electrochemistry has a wide range of applications. Research and describe one job, outside the field of chemistry, that uses electrochemical knowledge.

Section 3.3 REVIEW

Section Summary

- A combustion reaction of a substance with oxygen produces one or more oxides. Energy, in the form of heat and light, is released.
- A hydrocarbon is a compound that is composed of only the elements hydrogen and carbon. The combustion of a hydrocarbon can be either complete or incomplete.
- The products of complete combustion reactions are carbon dioxide and water vapour.
- The products of incomplete combustion reactions include carbon, carbon monoxide, carbon dioxide, and water vapour.
- Some reactions are both a combustion reaction and a synthesis reaction.

Review Questions

1. K/U In a laboratory investigation, what evidence might indicate that a combustion reaction is occurring?

2. K/U Identify three hydrocarbons that are used as fuels and undergo combustion reactions.

3. C Create a flowchart to describe how you would correctly adjust the air vents on a laboratory burner.

4. T/I A student says that $C_{12}H_{22}O_{11}(s)$ is a type of hydrocarbon. Do you agree? Explain your answer.

5. T/I Identify the missing product in the following balanced chemical equation for the complete combustion of pentane:

$C_5H_{12}(\ell) + 8O_2(g) \rightarrow$ _____ $+ 6H_2O(g)$

6. T/I Write a balanced chemical equation for the complete combustion of each hydrocarbon.

a. ethene, $C_2H_4(g)$

b. decane, $C_{10}H_{22}(\ell)$

c. butene, $C_4H_8(g)$

d. hexane, $C_6H_{14}(\ell)$

7. T/I Would the presence of excess oxygen cause hazardous products to be formed during combustion? Explain your reasoning.

8. K/U Is the combustion reaction shown in **Figure 3.23** likely to be producing soot? Explain your answer.

9. T/I Refer to **Figure 3.26**.

a. In the reactions shown in the photographs, what types of energy are being released?

b. What types of chemical products are being formed?

10. A Carbon monoxide poisoning can be lethal.

a. What type of chemical reaction produces carbon monoxide?

b. What are the early signs of carbon monoxide poisoning?

c. Why can prolonged exposure lead to death?

11. A The photograph below shows a device that is designed to protect people from a toxic gas.

a. What gas is the device made to detect?

b. In what type of reaction is this gas likely to be formed?

12. K/U Why is it not possible to balance a chemical equation representing incomplete combustion without having additional information about the reaction?

13. C Create a Venn diagram to compare complete combustion of hydrocarbons with incomplete combustion of hydrocarbons.

14. K/U What causes a candle flame to appear yellow?

15. T/I Classify each reaction as a synthesis or combustion reaction, or both. Give reasons for your classification.

a. $2Ca(s) + O_2(g) \rightarrow 2CaO(s)$

b. $2C_4H_{10}(g) + 13O_2(g) \rightarrow 8CO_2(g) + 10H_2O(g)$

c. $6K(s) + N_2(g) \rightarrow 2K_3N(s)$

16. A What would happen to a living organism if its cells were no longer able to carry out the series of reactions that make up cellular respiration?