SECTION 12.1

The Combined Gas Law

Key Terms

combined gas law
law of combining volumes
Avogadro's law (hypothesis)
molar volume
standard temperature and pressure (STP)
standard ambient temperature and pressure (SATP)

In a roadway accident, the pressure in an air bag, such as the one shown in **Figure 12.1**, can save lives. How can enough pressure be generated within milliseconds after a collision to prevent a person from injury? When a collision occurs, a sensor activates an electrical circuit that triggers a chemical reaction inside the air bag. The reaction produces about 65 L of nitrogen gas that inflates the air bag almost instantaneously. As soon as a person's body hits the air bag, the bag starts to deflate, cushioning the impact. The nitrogen gas escapes through vents in the bag, and within two seconds, the pressure inside the bag returns to atmospheric pressure.

If you analyze the process that occurs in an air bag, you discover that the temperature, pressure, and volume of the system all change significantly and at the same time. In Chapter 11, you studied the gas laws by considering only two of these variables at a time. However, in most situations that involve gases—in nature, as well as in industrial processes—all three variables change together. Therefore, developing a method to monitor simultaneous changes in the temperature, pressure, and volume of a gas is essential for studying and making accurate predictions of gas behaviour.

The Combined Gas Law

The combined gas law represents a combination of the relationships that express Boyle's law and Charles's law. The **combined gas law** states that the pressure and volume of a given amount of gas are inversely proportional to each other, and directly proportional to the Kelvin temperature of the gas.

combined gas law a gas law stating that the pressure and volume of a given amount of gas are inversely proportional to each other and directly proportional to the Kelvin temperature of the gas: $V \alpha \frac{T}{P}$

The combined gas law is represented by the following equation, where T is the Kelvin temperature and assuming that the amount of gas remains constant.

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

Figure 12.1 The usefulness of air bags depends on the simultaneous changes in the temperature, pressure, and volume of the gas.

Calculations Using the Combined Gas Law

The combined gas law is a useful tool for making predictions that involve a constant amount of gas and any of the three variables—temperature, pressure, or volume. For example, imagine that you prepare a gas in a laboratory apparatus that allows you to alter the pressure and temperature of the gas. You could use the combined gas law to predict the change in volume of a fixed amount of gas that results from changes in temperature and pressure.

The following Sample Problems and Practice Problems will reinforce your understanding of the combined gas law.

Sample Problem

Determining Volume Using the Combined Gas Law

Problem

A small balloon contains 275 mL of helium gas at a temperature of 25.0°C and a pressure of 350 kPa. What volume would this gas occupy at 10.0°C and 101 kPa?

What Is Required?

You need to find the volume, V_2, of the balloon under the new conditions of temperature and pressure.

What Is Given?

You know the initial pressure, volume, and temperature:

$P_1 = 350$ kPa
$V_1 = 275$ mL
$T_1 = 25.0$°C

You also know the final temperature and pressure:

$T_2 = 10.0$°C
$P_2 = 101$ kPa

Plan Your Strategy	Act on Your Strategy
According to the combined gas law relationship, changes in the temperature and pressure of a gas cause a change in its volume.	$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$
Convert temperatures from the Celsius scale to the Kelvin scale.	$T_1 = 25.0°\text{C} + 273.15$ $= 298.15$ K $T_2 = 10.0°\text{C} + 273.15$ $= 283.15$ K
Isolate the variable V_2.	$\frac{P_1V_1}{T_1}\left(\frac{T_2}{P_2}\right) = \frac{\cancel{P_2}V_2}{\cancel{T_2}}\left(\frac{\cancel{T_2}}{\cancel{P_2}}\right)$ $\frac{P_1V_1T_2}{T_1P_2} = V_2$
Substitute numbers and units for the known variables in the formula and solve.	$V_2 = \frac{P_1V_1T_2}{T_1P_2}$ $= \frac{(350\ \cancel{\text{kPa}})(275\ \text{mL})(283.15\ \cancel{\text{K}})}{(298.15\ \cancel{\text{K}})(101\ \cancel{\text{kPa}})}$ $= 910$ mL

Continued on next page

Alternative Solution

Plan Your Strategy	Act on Your Strategy
You know that the volume increases when the pressure decreases. Determine the ratio of the initial pressure and the final pressure that is greater than 1.	$P_1 = 350$ kPa $P_2 = 101$ kPa pressure ratio >1 is $\frac{350\text{ kPa}}{101\text{ kPa}}$
Convert temperatures from the Celsius scale to the Kelvin scale. You know that the volume decreases when temperature decreases. Determine the ratio of the initial temperature and the final temperature that is less than 1. Convert temperatures from the Celsius scale to the Kelvin scale.	$T_1 = 25.0°\text{C} + 273.15$ $= 298.15$ K $T_2 = 10.0°\text{C} + 273.15$ $= 283.15$ K temperature ratio < 1 is $\frac{283.15\text{ K}}{298.15\text{K}}$
Multiply the initial volume by the pressure and temperature ratios to obtain the final volume.	$V_2 = V_1 \times$ pressure ratio $\times$ temperature ratio $= 275\text{ mL} \times \frac{350\text{ kPa}}{101\text{ kPa}} \times \frac{283.15\text{ K}}{298.15\text{ K}}$ $= 910$ mL

Check Your Solution

The large decrease in pressure would cause a large increase in volume. Since the temperature decreased slightly, it should cause only a slight decrease in volume. Thus, you would expect a significant overall increase in volume.

Practice Problems

1. A sample of argon gas, Ar(g), occupies a volume of 2.0 L at −35°C and 0.5 atm. What would its Celsius temperature be at 2.5 atm if its volume was decreased to 1.5 L?
2. A chemical researcher produces 15.0 mL of a new gaseous substance in a laboratory at a temperature of 298 K and pressure of 100.0 kPa. Calculate the volume of this gas if the temperature was changed to 273 K and the final pressure was 101.325 kPa.
3. A sample of air in a syringe exerts a pressure of 1.02 atm at 295 K. The syringe is placed in a boiling water bath at 373 K. The pressure is increased to 1.23 atm and the volume becomes 0.224 mL. What was the initial volume?
4. Helium gas, He(g), in a 1.0×10^2 L weather balloon is under a pressure of 25 atm at 20.0°C. If the helium balloon expands to 2400 L at 1.05 atm of pressure, what would the temperature of the helium gas be?
5. A 30.00 mL gas syringe was at a pressure of 100.0 kPa at 30.0°C. On the following day, the temperature dropped to 25.0°C and the new volume was 28.5 mL. What was the atmospheric pressure on this day?
6. A 2.7 L sample of nitrogen gas, $N_2(g)$, is collected at a temperature of 45.0°C and a pressure of 0.92 atm. What pressure would have to be applied to the gas to reduce its volume to 2.0 L at a temperature of 25.0°C?
7. A scuba diver is swimming 30.0 m below the ocean surface where the pressure is 4.0 atm and the temperature is 8.0°C. A bubble of air with a volume of 5.0 mL is emitted from the breathing apparatus. What will the volume of the air bubble be when it is just below the surface of the water, where the pressure is 101.3 kPa and the water temperature is 24.0°C?
8. A 5.0×10^2 mL sample of oxygen, $O_2(g)$, is kept at 950 mmHg and 21.5°C. The oxygen expands to a volume of 700 mL and the temperature is adjusted until the pressure is 101.325 kPa. Calculate the final temperature of the oxygen gas.
9. A sample of Freon-12, $CF_2Cl_2(g)$, formerly used in refrigerators, is circulated through a series of pipes for refrigeration. If the gas occupies 350 cm^3 at a pressure of 150 psi and a temperature of 15°C, what volume of gas will be released if there is a break in the line where the external temperature is 25°C and the external pressure is 102 kPa?
10. A crack in the floor of the ocean at a depth where the pressure is 16 atm releases 350 m^3 of methane gas. The temperature of the water at this depth is 8°C. If the surface temperature is 40°C and the pressure is 758 mmHg, what volume of methane is released at the surface?

Combining Volumes of Gases

Many of the first studies of gases focussed on the relationships among the volume, pressure, and temperature for a particular mass of the gas sample. By the early 1800s, scientists were exploring chemical reactions between gases. Gay-Lussac and a colleague, Alexander von Humboldt (1769–1859), performed experiments to determine the number of volumes of hydrogen and of oxygen that would react to form a volume of water. They needed this information to determine the percentage of oxygen in the atmosphere. By making precise measurements, Gay-Lussac determined that two volumes of hydrogen combined with one volume of oxygen to form two volumes of water.

From studying the volumes of other gases in other chemical reactions, Gay-Lussac reached the general conclusion that, in chemical reactions, all gases combine in simple proportions. This conclusion is now known as the **law of combining volumes**, which states that when gases react, the volumes of the gaseous reactants and products, measured under the same conditions of temperature and pressure, are always in whole-number ratios. Shown below are examples of gas volumes before and after chemical reactions to illustrate the law of combining volumes. All gas volumes are measured at the same temperature and pressure.

law of combining volumes a gas law stating that when gases react, the volumes of the gaseous reactants and products, measured under the same conditions of temperature and pressure, are always in whole-number ratios

Example 1: The reaction between hydrogen gas and oxygen gas

hydrogen gas + oxygen gas → water vapour

100 mL + 50 mL → 100 mL

Example 2: The decomposition of ammonia gas, $NH_3(g)$

ammonia gas → hydrogen gas + nitrogen gas

8 mL → 12 mL + 4 mL

Avogadro's Law

A few years before Gay-Lussac's description of combining gas volumes, English scientist John Dalton had published his ideas about atoms combining in simple, whole-number ratios to form compounds. Empirical work on the mass percent of elements present in compounds suggested that chemical combinations of the same elements always occurred in fixed mass ratios or multiples of those ratios. For example, water is always 88.89 percent oxygen and 11.11 percent hydrogen by mass. Thus, the mass of oxygen in a water molecule is eight times the mass of hydrogen in a water molecule. However, chemists at that time could not understand how one volume of oxygen could combine with two volumes of hydrogen to form two volumes of water vapour if the mass of oxygen in water was eight times the mass of hydrogen in water.

Italian scientist Amadeo Avogadro (1776–1856) resolved the apparent conflict between Gay-Lussac's and Dalton's observations. In 1811, he proposed that the law of combining volumes could be explained if equal volumes of gases contained the same number of particles, regardless of their mass. Avogadro's proposal was ignored for 50 years, because scientists could not accept such a revolutionary idea. Eventually, however, scientists realized the significance of the proposal and more observations supported it. Avogadro's proposal is now known as **Avogadro's law**. You also may see it called *Avogadro's hypothesis*. Either way, chemists now understand that the volume of a gas is directly proportional to the number of molecules of the gas, when the pressure and temperature are constant.

Avogadro's law (hypothesis) a gas law stating that equal volumes of all ideal gases at the same temperature and pressure contain the same number of molecules

The Mole in Relation to Gas Volume

You know that a large number of molecules are required to produce measurable volumes and masses of substances in the laboratory. Recall that Avogadro's number, 6.02×10^{23} particles, represents 1 mol of those particles. When the particles are molecules, the ratio of the amounts of the substances present, expressed in moles, is equal to the ratio of the coefficients of the substances in a balanced chemical equation. **Figure 12.2** shows how amounts of gases, expressed in moles, are related to volumes of gases in chemical reactions.

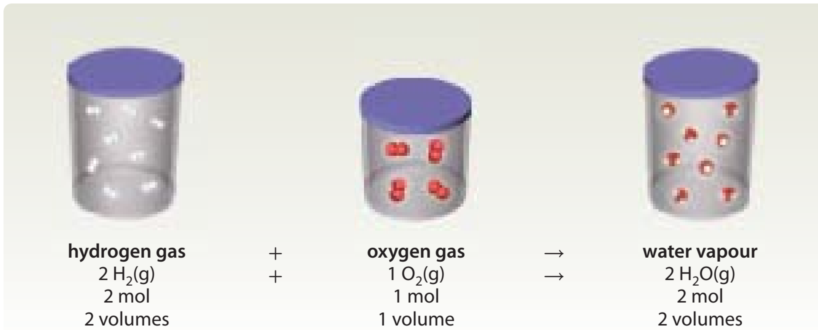


Figure 12.2 The coefficients in a balanced equation show the relationships between the amounts (in moles) of all reactants and products, and the relationships between the volumes of any gaseous reactant or product.

Using the Law of Combining Volumes to Determine the Stoichiometry of a Chemical Reaction

According to the law of combining volumes, when gases react the volumes of the gaseous reactants and products, measured at the same conditions of temperature and pressure, are always in whole-number ratios. Also recall that, when a chemical reaction involves only gaseous reactants and products, the mole ratios are the same as the ratios of the volumes of the gases. Therefore, the principles of the law of combining volumes can be used to determine the volume of a gaseous reactant or product based on the volume of another gaseous reactant or product.

To determine the volume of a gaseous reactant or product in a reaction, you must know the balanced chemical equation for the reaction and the volume of at least one of the gases involved in the reaction. Consider, for example, the combustion of methane gas, shown in **Figure 12.3**. This reaction takes place every time you light a Bunsen burner, since natural gas is composed of mostly methane. Because the coefficients represent volume ratios for gases taking part in the reaction, you can determine that it takes 2 L of oxygen to react completely with 1 L of methane. The complete combustion of 1 L of methane will produce 1 L of carbon dioxide and 2 L of water vapour. Note that the conditions of temperature and pressure are not mentioned. When using the law of combining volumes to solve gas stoichiometry problems, the temperature and pressure must be the same for the reactants and products.

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

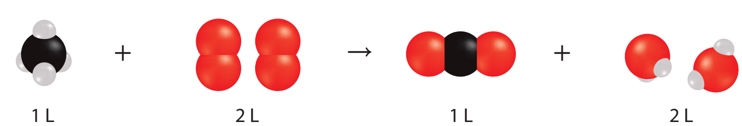


Figure 12.3 From the coefficients of the balanced chemical equation, volume ratios can be set up for any pair of gases in the reaction.

A Mathematical Statement of Avogadro's Law

The amount (in moles) of a substance consists of a specific number of molecules. Thus, Avogadro's law can be expressed in moles. These steps develop a mathematical expression for Avogadro's law, in which n represents the amount (in moles) of the gas.

When the temperature and pressure of a gas are constant, Avogadro's law can be expressed mathematically as a proportionality.	$n \propto V$
By using a proportionality constant, k, Avogadro's law can also be expressed as an equality.	$n = kV$
As long as the temperature and pressure of a gas remain constant, any combination of the gas amount (in moles) divided by the volume of the gas is equal to the same constant.	$\frac{n_1}{V_1} = k$ and $\frac{n_2}{V_2} = k$
Combining the expressions gives a mathematical statement of Avogadro's law.	$\frac{n_1}{V_1} = \frac{n_2}{V_2}$

Figure 12.4 depicts Avogadro's law by showing how an increase in the amount (n) of a gas at constant temperature and pressure causes the volume to increase.

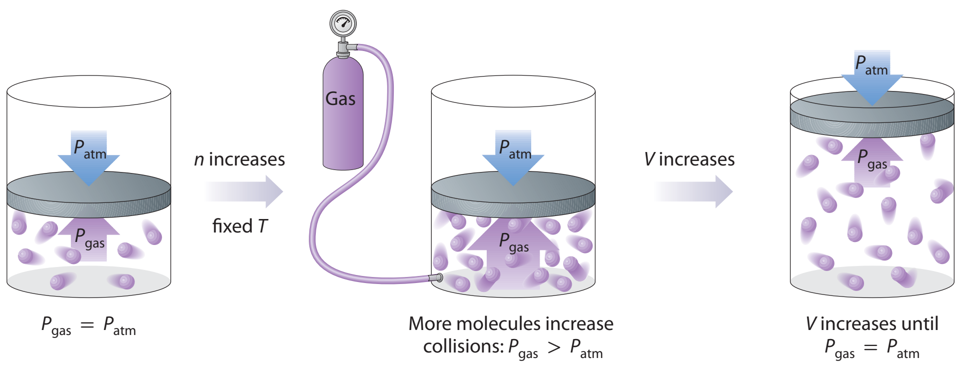


Figure 12.4 When more gas enters a container, the increase in the number of molecules causes the pressure to increase. Because the pressure inside the container is greater than the external pressure at constant temperature, the volume will increase. The volume will continue to increase until the internal pressure caused by the gas becomes equal to the external pressure.

Learning Check

1. What gas laws comprise the combined gas law?
2. In your own words, describe the law of combining volumes.
3. A sample of gas has a volume of 525 mL at 300.0 K and 746 mmHg. What is the volume of the gas if the temperature increases to 350.0 K and the pressure increases to 780 mmHg?
4. When predicting volumes of gaseous reactants and products, why must a balanced equation be used?
5. Butene gas, $C_4H_8(g)$, burns in the presence of oxygen to produce gaseous carbon dioxide and water vapour.
   a. Using this reaction, define and explain the law of combining volumes of gases.
   b. Calculate the volume of butene required to produce 250 mL of carbon dioxide. Assume temperature and pressure remain constant.
6. Use the mathematical expression for Avogadro's law to determine the volume of 1.0 mol of a gas if a 2.0 mol sample of the gas has a volume of 30.0 L. Assume temperature and pressure remain constant.

The Molar Volume of Gases

molar volume amount of space occupied by 1 mol of a gaseous substance; 22.4 L/mol for an ideal gas at standard temperature and pressure and 24.8 L/mol for an ideal gas at standard ambient temperature and pressure

standard temperature and pressure (STP) conditions defined as a temperature of 0°C (273.15 K) and a pressure of 101.325 kPa

standard ambient temperature and pressure (SATP) conditions defined as a temperature of 25°C (298 K) and a pressure of 100 kPa

According to Avogadro's law, the volume of 1 mol of any gas should be the same as the volume of 1 mol of any other gas, if the conditions of temperature and pressure are the same. Thus, it is possible to calculate the **molar volume (v)** of a gas, or the volume of 1 mol of a gas. Molar volume is expressed in units of L/mol, which can be found by dividing the volume, V, by the amount in moles, n, present:

$$v = \frac{V}{n}$$

Molar volume will vary with different temperatures and pressures. Atmospheric pressure and ambient temperature (the temperature of the surrounding air) can vary from one place to another. They also can vary in the same location at different times of the day. Therefore, chemists have agreed on specific sets of conditions under which to report gas volumes. One of these is called **standard temperature and pressure (STP)**, defined as a temperature of 0°C (273.15 K) and a pressure of 1 atm (101.325 kPa).

STP values approximate the freezing point of water and atmospheric pressure at sea level. However, these are not the most comfortable conditions in which to make measurements. Thus, a second specific set of conditions that resembles the conditions in a more comfortable environment, such as a laboratory, has been devised. This second set of conditions is called **standard ambient temperature and pressure (SATP)**, defined as a temperature of 25°C (298.15 K) and a pressure of 100 kPa. **Table 12.1** summarizes the standard conditions of temperature and pressure, as well as the calculated molar volumes of an ideal gas at these conditions.

Table 12.1 Standard Conditions of Temperature and Pressure

Conditions	Pressure	Celsius Temperature	Kelvin Temperature	Molar Volume of an Ideal Gas
STP	101.325 kPa	0°C	273.15 K	22.4 L/mol
SATP	100.0 kPa	25°C	298.15 K	24.8 L/mol

Molar volumes at STP have been experimentally determined for many gases. Examples are provided in **Table 12.2**. Notice how the values in **Table 12.2** are approximately 22.4 L/mol, which is the molar volume of an ideal gas at STP. Therefore, 22.4 L/mol is often used in calculations involving the molar volume of a gas. When you are doing calculations for SATP conditions, the standard molar volume to use is 24.8 L/mol.

Table 12.2 Experimentally Determined Molar Volumes of Gases at STP

Gas	Molar Volume (L/mol)
helium	22.398
neon	22.401
argon	22.410
hydrogen	22.430
nitrogen	22.413
oxygen	22.414
carbon dioxide	22.414
ammonia	22.350

In the Sample Problems and Practice Problems that appear on the following pages, you will learn how to use and calculate the molar volume of a gas under STP conditions and SATP conditions.

Activity 12.1 Molar Volumes of Gases

Students performed a series of measurements to determine the molar masses of three different gases. Their results are in the table below. Note: the temperature in the room was 23.0°C (296.15 K), and the pressure was 98.7 kPa.

Measurements of Three Gases

Measurement	Carbon Dioxide	Oxygen	Methane
Volume of gas (V)	150 mL	150 mL	150 mL
Mass of empty syringe	25.08 g	25.08 g	25.08 g
Mass of gas + syringe	25.34 g	25.27 g	25.18 g
Mass of gas (m)			
Molar mass of gas (M)			
Amount (in moles) of gas $\left(n = \frac{m}{M}\right)$			

Procedure

1. Copy and complete the table. Calculate the molar volume of each gas at the experimental conditions.
2. Using the combined gas law, determine the volume of each gas at STP. Using those values, calculate the molar volume of each gas at STP.

Questions

1. Compare the molar volumes at STP with those for the experimental conditions. What do you observe for each gas?
2. Compare the three molar volumes at STP. What do you notice?

Sample Problem

Using Avogadro's Law to Find the Quantity of a Gas

Problem

At STP, 1 mol of oxygen gas has a volume of 22.4 L. Determine the mass and number of molecules in a 44.8 L sample of the gas.

What Is Required?

You need to find the mass and number of molecules of a sample of oxygen gas.

What Is Given?

You know the initial amount of the gas, as well as the initial and final volumes:

$V_1 = 22.4\text{ L}$

$n_1 = 1\text{ mol}$

$V_2 = 44.8\text{ L}$

You also know the molar mass of $O_2(g)$: $2 \times 16.00\text{ g/mol} = 32.00\text{ g/mol}$

Algebraic Method

Plan Your Strategy	Act on Your Strategy
Use Avogadro's law and solve for the amount (in moles) of oxygen.	$\frac{n_1}{V_1} = \frac{n_2}{V_2}$ $n_2 = \frac{n_1V_2}{V_1} = \frac{1.00\text{ mol} \times 44.8\cancel{\text{L}}}{22.4\cancel{\text{L}}} = 2.00\text{ mol}$
Calculate the mass of oxygen by using the amount (in moles) and the molar mass of oxygen.	$m = n \times M$ $= 2.00\cancel{\text{mol}} \times 32.00\text{ g}/\cancel{\text{mol}} = 64.0\text{ g}$
Calculate the number of molecules by multiplying the amount (in moles) by the Avogadro constant.	number of molecules $= 2.00\cancel{\text{mol}} \times 6.02 \times 10^{23}$ molecules/$\cancel{\text{mol}}$ $= 1.20 \times 10^{24}$ molecules

Check Your Solution

The volume of oxygen is double the volume of 1 mol of gas, so it makes sense that 2 mol of oxygen and twice the number of molecules are present.

Sample Problem

Calculating the Molar Volume of Nitrogen

Problem

An empty, sealed container has a volume of 0.652 L and a mass of 2.50 g. When filled with nitrogen gas, the container has a mass of 3.23 g. The pressure of the nitrogen in the container is 97.5 kPa when the temperature is 21.0°C. Calculate the molar volume of nitrogen gas at STP.

What Is Required?

You need to find the molar volume, v, of 1 mol of nitrogen gas at STP.

What Is Given?

You know the initial temperature, pressure, and the volume of the gas, as well as the mass of the container when empty and when filled with nitrogen:

$T_1 = 21.0°C$, or $T_1 = 294.15$ K
$P_1 = 97.5$ kPa
$V_1 = 0.652$ L

Mass of the container = 2.50 g
Mass of the container + nitrogen = 3.23 g

You also know the conditions of STP and the molar mass of nitrogen:

$T_2 = 0°C$, or 273.15 K

$P_2 = 101.325$ kPa

Molar mass of $N_2(g) = 2 \times 14.01$ g/mol = 28.02 g/mol

Plan Your Strategy	Act on Your Strategy
Find the mass of the nitrogen in the container by subtracting the mass of the empty container from the mass of the container filled with nitrogen gas.	$m_{nitrogen} = m_{container} - m_{vacuum}$ $= 3.23 \text{ g} - 2.50 \text{ g}$ $= 0.73 \text{ g}$
Calculate the amount (in moles) of nitrogen by using the formula $n = \frac{m}{M}$, where m = mass of nitrogen and M = molar mass of nitrogen.	$n = \frac{m}{M}$ $= \frac{0.73 \cancel{\text{g}}}{28.02 \cancel{\text{g}}/\text{mol}} = 0.026053 \text{ mol}$
Use the combined gas law to find the volume, V_2, that the nitrogen would occupy at STP.	$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$ $\frac{P_1V_1}{T_1}\left(\frac{T_2}{P_2}\right) = \frac{\cancel{P_2}V_2}{\cancel{T_2}}\left(\frac{\cancel{T_2}}{\cancel{P_2}}\right)$ $V_2 = \frac{P_1V_1T_2}{T_1P_2}$ $= \frac{(97.5 \cancel{\text{kPa}})(0.652 \text{ L})(273.15 \cancel{\text{K}})}{(294.15 \cancel{\text{K}})(101.325 \cancel{\text{kPa}})} = 0.582597 \text{ L}$
Find the volume of 1 mol of nitrogen at STP by dividing the amount (in moles) of nitrogen by the volume of nitrogen at STP.	$v = \frac{V}{n}$ $= \frac{V_2}{n}$ $= \frac{0.582597 \text{ L}}{0.026053 \text{ mol}}$ $= 22.4 \text{ L/mol}$

Alternative Solution

Plan Your Strategy	Act on Your Strategy
Calculate the amount (in moles) of nitrogen by using the molar mass and the mass of nitrogen (0.73 g).	$n = \frac{m}{M}$ $= \frac{0.73\ \cancel{g}}{28.02\ \cancel{g}/\text{mol}} = 0.026053\ \text{mol}$
You know that the volume decreases when the pressure increases. Determine the ratio of the initial pressure and the final pressure that is less than 1. You know that a decrease in temperature also causes a decrease in volume. Determine the ratio of the initial temperature and the final temperature that is less than 1.	$P_1 = 97.5$ kPa $P_2 = 101.325$ kPa pressure ratio < 1 is $\frac{97.5\ \text{kPa}}{101.325\ \text{kPa}}$ $T_1 = 294.15$ K $T_2 = 273.15$ K temperature ratio < 1 is $\frac{273.15\ \text{K}}{294.15\ \text{K}}$
Multiply the initial volume by the pressure and temperature ratios to obtain the final volume of nitrogen gas.	$V_2 = V_1 \times$ pressure ratio $\times$ temperature ratio $= 0.652\ \text{L} \times \frac{97.5\ \cancel{\text{kPa}}}{101.325\ \cancel{\text{kPa}}} \times \frac{273.\cancel{15}\ \text{K}}{294.\cancel{15}\ \text{K}}$ $= 0.582597$ L
There is less than 1 mol of nitrogen gas present, so the molar volume (the volume of 1 mol of nitrogen gas) will be greater than the volume that you calculated above. To find the molar volume, multiply by a mole ratio that is greater than 1. The molar volume, v, is equal to the volume calculated divided by 1.00 mol.	mole ratio > 1 is $\frac{1\ \text{mol}}{0.026053\ \text{mol}}$ volume of 1 mol $= V_2 \times$ mol ratio $= (0.582597\ \text{L}) \times \frac{1\ \cancel{\text{mol}}}{0.026053\ \cancel{\text{mol}}}$ $= 22.4$ L Therefore, $v = 22.4$ L/mol

Check Your Solution

The answer is expressed in the correct units and it agrees with the accepted molar volume value.

Practice Problems

11. At STP, 1.0 mol of carbon dioxide gas has a volume of 22.41 L. What mass of carbon dioxide is present in 3.0 L?

12. At STP, 1.0 mol of nitrogen gas occupies a volume of 22.41 L. Find the volume that 15.50 g of nitrogen gas occupies at STP.

13. Find the volume that 20.0 g of carbon monoxide gas, CO(g), occupies at SATP.

14. An experiment generates 0.152 g of hydrogen gas. What volume of gas was generated at STP?

15. A solid block of carbon dioxide has a mass of 2.50×10^2 g. Once the block has totally sublimated, what volume would it occupy at SATP?

16. A commercial refrigeration unit accidentally releases 12.5 L of ammonia gas at SATP. Determine the mass and number of molecules of ammonia gas released.

17. A 6.98 g sample of chlorine gas has a volume of 2.27 L at 0.0°C and 1.0 atm. Find the molar volume of the chlorine gas at 25°C and 100.0 kPa.

18. A sample of helium gas has a mass of 11.28 g. At STP, the sample has a volume of 63.2 L. What is the molar volume of this gas at 32.2°C and 98.1 kPa?

19. Magnesium, Mg(s), was reacted with hydrochloric acid, HCl(aq), in excess according to the following equation:

$$Mg(s) + 2HCl(aq) \rightarrow MgCl_2(aq) + H_2(g)$$

When 0.0354 g of magnesium was reacted, 35.63 mL of hydrogen gas was collected.

a. How many moles of magnesium were reacted?
b. How many moles of hydrogen were collected?
c. If the hydrogen gas was collected at 20.0°C and 99.5 kPa, determine the molar volume of hydrogen gas from the experimental data.

20. Helium has a density of 0.179 g/L at STP. Calculate its molar volume at these conditions.

Section 12.1 REVIEW

Section Summary

- Gases can undergo changes in temperature, pressure, and volume simultaneously. The combined gas law addresses these changes and is represented mathematically as

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

- The law of combining volumes states that, when gases react, the volumes of the gaseous reactants and products, measured under the same conditions of temperature and pressure, are always in whole-number ratios.
- If the temperature and pressure are constant and the same for the reactants and products of a chemical reaction, the law of combining volumes can be used to determine the amounts of reactant and/or products.
- Avogadro proposed that, under the same conditions of temperature and pressure, equal volumes of all ideal gases contain the same number of molecules, even though they do not have the same mass. A mathematical statement of Avogadro's law is

$$\frac{n_1}{V_1} = \frac{n_2}{V_2}$$

Review Questions

1. T/I A weather balloon is released. If you know the initial volume, temperature, and air pressure, what information will you need to predict the balloon's volume when it reaches its final altitude?

2. K/U Based on the combined gas law, will the volume of a fixed amount of gas increase, decrease, or remain the same for each of the following changes. Explain each answer.

a. The pressure is decreased from 2 atm to 1 atm; the temperature is decreased from 200°C to 100°C.

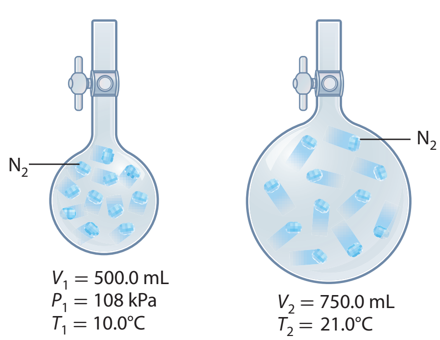
b. The pressure is increased from 1 atm to 4 atm, while the temperature is increased from 100°C to 200°C.

c. The pressure is increased from 0.5 atm to 1.0 atm; the temperature is decreased from 250°C to 100°C.

3. A Explain how the combined gas law could be applied to the use of weather balloons.

4. T/I A sample of argon gas occupies a volume of 2.0 L at −35°C and standard atmospheric pressure. What would its Celsius temperature be at 2.0 atm if its volume decreased to 1.5 L? Assume the amount of gas remains constant.

5. T/I Consider the diagram below. What is the pressure of the nitrogen gas in the flask on the right , assuming the amount of gas remains constant?



6. T/I A propane tank has a volume of 76 L and is at a temperature of 25°C and a pressure of 1500 kPa. Gas is discharged at a rate of 5 mL/min at a pressure of 100 kPa and temperature of 30°C. How long will it take for the tank to empty?

7. K/U If the volume of 1.0 mol of helium at 37°C and 90.0 kPa is 29 L, what will be the volume of 1.0 mol of nitrogen at the same temperature and pressure? Explain your reasoning.

8. T/I If all reactants are at the same temperature and pressure, what volume of oxygen gas is required for 15 L of methane to undergo complete combustion?

9. T/I Nitrogen gas reacts with oxygen gas to produce nitrogen dioxide gas. What volume of nitrogen dioxide gas is formed when 350 mL of nitrogen gas reacts with an excess of oxygen gas?

10. K/U In your own words, describe Avogadro's law.

11. T/I A balloon filled with helium gas, He(g), develops a leak. If it originally contained 0.20 mol of gas and had a volume of 3.5 L, how many moles of gas are remaining when the balloon has a volume of 2.5 L?

12. T/I Determine the following for a 10.0 L sample of argon gas at STP.

a. the amount (in moles) of argon present

b. the mass (in grams) of argon present

c. the number of molecules of argon

d. the molar volume

13. C Use a graphic organizer to distinguish between the terms STP and SATP, and explain the value of defining and using these standards.

14. T/I What is the molar volume of hydrogen gas at 255°C and 102 kPa, if a 1.09 L volume of the gas has a mass of 0.0513 g?