3. Dalton's law works well for any gases that behave similarly to the "ideal" gas — that have small molecules and low intermolecular forces, and do not react.
4. Dalton's law can be explained by two concepts: gas particles act independently; and pressure is caused by particle collisions with the walls of the container.
5. Dalton's law works perfectly only for "ideal" gases; but to three significant digits, for most common gases, it works well.

Making Connections

6. Possibilities include the gradual absorption of emitted gases by physical, geological, and biological processes. For example, carbon dioxide dissolves in water (oceans), and is used by plants to generate sugars through photosynthesis. The carbon in the gas can be followed through biological processes until it is deposited as sediment and buried, eventually forming limestone.

Reflecting

7. Diagrams drawn by students should show the principle illustrated in Figure 2, in a similar fashion. The adding of amounts must be shown as proportional to the adding of pressures.
   Visual models are much easier for most people to understand than mathematical models.

10.2 REACTIONS OF GASES

PRACTICE

(Page 468)

Understanding Concepts

1. Avogadro's theory was needed to relate reacting volumes to equations.
2. Avogadro used empirical observations of coefficient values from equations, and reacting volume ratios of gases.
3. $C_3H_{8(g)} \quad + \quad 5\ O_{2(g)} \quad \rightarrow \quad 3\ CO_{2(g)} \quad + \quad 4\ H_2O_{(g)}$

   5.00 L $\qquad$ v

   Pressure and temperature conditions equal for all gases measured.

   $v_{O_2} = 5.00\ L \times \frac{5}{1}$

   $v_{O_2} = 25.0\ L$

or *Note:* The text example on page 468 uses a mole ratio for conversion, but the volume ratio shown here is more appropriate.

   $v_{O_2} = 5.00\ \cancel{L}\ \cancel{C_3H_8} \times \frac{5\ L\ O_2}{1\ \cancel{L}\ \cancel{C_3H_8}}$

   $v_{O_2} = 25.0\ L$

   The volume of oxygen required is 25.0 L.
4. $2\ NO_{(g)} \quad + \quad 2\ H_{2(g)} \quad \rightarrow \quad N_{2(g)} \quad + \quad 2\ H_2O_{(g)}$

   1.2 L $\qquad\qquad$ v

   Pressure and temperature conditions equal for all gases measured.

   $v_{N_2} = 1.2\ L \times \frac{1}{2}$

   $v_{N_2} = 0.60\ L$

or

   $v_{N_2} = 1.2\ \cancel{L}\ \cancel{NO} \times \frac{1\ L\ N_2}{2\ \cancel{L}\ \cancel{NO}}$

   $v_{N_2} = 0.60\ L$

   The volume of nitrogen produced is 0.60 L.

5. (a) $16\ H_2S_{(g)} + 8\ SO_{2(g)} \rightarrow 3\ S_{8(s)} + 16\ H_2O_{(g)}$

248 kL $\quad$ v

All gases measured at 250 kPa and 350°C.

$$v_{SO_2} = 248\ \text{kL} \times \frac{8}{16}$$

$$v_{SO_2} = 124\ \text{kL}$$

or

$$v_{SO_2} = 248\ \text{k}\cancel{\text{L}}\ \cancel{H_2S} \times \frac{8\ \text{L}\ SO_2}{16\ \cancel{\text{L}}\ \cancel{H_2S}}$$

$$v_{SO_2} = 124\ \text{kL}$$

The volume of sulfur dioxide needed is 124 kL.

(b) $S_{8(s)} + 8\ O_{2(g)} \rightarrow 8\ SO_{2(g)}$

v $\quad$ 250 kL

All gases measured at 200 kPa and 450°C.

$$v_{O_2} = 250\ \text{kL} \times \frac{8}{8}$$

$$v_{O_2} = 250\ \text{kL}$$

or

$$v_{O_2} = 250\ \text{k}\cancel{\text{L}}\ \cancel{SO_2} \times \frac{8\ \text{L}\ O_2}{8\ \cancel{\text{L}}\ \cancel{SO_2}}$$

$$v_{O_2} = 250\ \text{kL}$$

The volume of oxygen required is 250 kL.

(c) $2\ SO_{2(g)} + O_{2(g)} \rightarrow 2\ SO_{3(g)}$

v $\quad$ v $\quad$ 325 kL

All gases measured at the same temperature and pressure conditions.

$$v_{SO_2} = 325\ \text{kL} \times \frac{2}{2}$$

$$v_{SO_2} = 325\ \text{kL}$$

or

$$v_{SO_2} = 325\ \text{k}\cancel{\text{L}}\ \cancel{SO_3} \times \frac{2\ \text{L}\ SO_2}{2\ \cancel{\text{L}}\ \cancel{SO_3}}$$

$$v_{SO_2} = 325\ \text{kL}$$

The volume of sulfur dioxide required is 325 kL.

$$v_{O_2} = 325\ \text{kL} \times \frac{1}{2}$$

$$v_{O_2} = 163\ \text{kL}$$

or

$$v_{O_2} = 325\ \text{k}\cancel{\text{L}}\ \cancel{SO_3} \times \frac{1\ \text{L}\ O_2}{2\ \cancel{\text{L}}\ \cancel{SO_3}}$$

$$v_{O_2} = 163\ \text{kL}$$

The volume of oxygen required is 163 kL.

Reflecting

6. The law of combining volumes is similar to the law of definite proportions in that it shows combination in integer ratios. It differs in that mass, and not volume, is compared; and also in that it does not apply to different substances in reactions, but only to compound substances formed from the same elements.

PRACTICE

(Page 471)

Understanding Concepts

7. $v_{SO_2} = 50 \text{ mL}$

   $V_{SATP} = 24.8 \text{ L/mol}$

   $n_{SO_2} = ?$

   $$n_{SO_2} = \frac{50 \cancel{\text{mL}} \times 1 \text{ mol}}{24.8 \cancel{\text{L}}}$$

   $$n_{SO_2} = 2.0 \text{ mmol}$$

   The amount of sulfur dioxide is 2.0 mmol.

8. (a) $n_{Ne} = 2.25 \text{ mol}$

   $V_{STP} = 22.4 \text{ L/mol}$

   $v_{Ne} = ?$

   $$v_{Ne} = 2.25 \cancel{\text{mol}} \times \frac{22.4 \text{ L}}{1 \cancel{\text{mol}}}$$

   $$v_{Ne} = 50.4 \text{ L}$$

   The volume of neon at STP is 50.4 L.

   (b) $p_1 = 101.325 \text{ kPa}$

   $T_1 = 0°\text{C} = 273 \text{ K}$

   $p_2 = ?$

   $T_2 = 35°\text{C} = 308 \text{ K}$

   $$\frac{p_1}{T_1} = \frac{p_2}{T_2}$$

   $$p_2 = \frac{p_1 T_2}{T_1}$$

   $$= \frac{101.325 \text{ kPa} \times 308 \cancel{\text{K}}}{}$$

   $$p_{Ne} = 114 \text{ kPa}$$

   or

   $$p_{Ne} = 101.325 \text{ kPa} \times \frac{308 \cancel{\text{K}}}{273 \cancel{\text{K}}}$$

   $$p_{Ne} = 114 \text{ kPa}$$

   The final pressure of the 50.4 L of warmed neon gas will be 114 kPa.

(c) The tube must be transparent to allow light from the neon to escape, and strong enough to hold the pressure of the gas when heated.

9. $m_{CO_2} = 0.13 \text{ g}$

   $V_{SATP} = 24.8 \text{ L/mol}$

   $M_{CO_2} = 44.01 \text{ g/mol}$

   $v_{CO_2} = ?$

   $$n_{CO_2} = 0.13 \cancel{\text{g}} \times \frac{1 \text{ mol}}{44.01 \cancel{\text{g}}}$$

   $$n_{CO_2} = 0.0030 \text{ mol}$$

$$v_{CO_2} = 0.0030\ \cancel{mol} \times \frac{24.8\ L}{1\ \cancel{mol}}$$
$$v_{CO_2} = 0.073\ L = 73\ mL$$

or

$$v_{CO_2} = 0.13\ \cancel{g} \times \frac{1\ \cancel{mol}}{44.01\ \cancel{g}} \times \frac{24.8\ L}{1\ \cancel{mol}}$$
$$v_{CO_2} = 0.073\ L = 73\ mL$$

The volume of carbon dioxide at SATP is 73 mL.

10. $m_{C_8H_{18}} = 50.0\ g$

$V_{STP} = 22.4\ L/mol$

$M_{C_8H_{18}} = 114.26\ g/mol$

$v_{C_8H_{18}} = ?$

$$n_{C_8H_{18}} = 50.0\ \cancel{g} \times \frac{1\ mol}{114.26\ \cancel{g}}$$
$$n_{C_8H_{18}} = 0.438\ mol$$
$$v_{C_8H_{18}} = 0.438\ \cancel{mol} \times \frac{22.4\ L}{1\ \cancel{mol}}$$
$$v_{C_8H_{18}} = 9.80\ L$$

or

$$v_{C_8H_{18}} = 50.0\ \cancel{g} \times \frac{1\ \cancel{mol}}{114.26\ \cancel{g}} \times \frac{22.4\ L}{1\ \cancel{mol}}$$
$$v_{C_8H_{18}} = 9.80\ L$$

The volume of octane vapour at STP would be 9.80 L.

11. $m_{NO_2} = 1.00\ Mg$

$V_{SATP} = 24.8\ L/mol$

$M_{NO_2} = 46.01\ g/mol$

$v_{NO_2} = ?$

$$n_{NO_2} = 1.00\ \cancel{Mg} \times \frac{1\ mol}{46.01\ \cancel{g}}$$
$$n_{NO_2} = 0.0217\ Mmol = 21.7\ kmol$$
$$v_{NO_2} = 21.7\ \cancel{kmol} \times \frac{24.8\ L}{1\ \cancel{mol}}$$
$$v_{NO_2} = 539\ kL$$

or

$$v_{NO_2} = 1.00\ \cancel{Mg} \times \frac{1\ \cancel{mol}}{46.01\ \cancel{g}} \times \frac{24.8\ L}{1\ \cancel{mol}}$$
$$v_{NO_2} = 0.539\ ML = 539\ kL$$

The volume of nitrogen dioxide at SATP would be 539 kL or 539 m^3.

12. $m_{H_2O} = ?$

$v = 1.00\ L$

$V_{SATP} = 24.8\ L/mol$

$$M_{H_2O} = 18.02 \text{ g/mol}$$

$$n_{H_2O} = 1.00 \cancel{\text{L}} \times \frac{1 \text{ mol}}{24.8 \cancel{\text{L}}}$$

$$n_{H_2O} = 0.0403 \text{ mol}$$

$$m_{H_2O} = 0.0403 \cancel{\text{mol}} \times \frac{18.02 \text{ g}}{1 \cancel{\text{mol}}}$$

$$m_{H_2O} = 0.727 \text{ g}$$

or

$$m_{H_2O} = 1.00 \cancel{\text{L}} \times \frac{1 \cancel{\text{mol}}}{24.8 \cancel{\text{L}}} \times \frac{18.02 \text{ g}}{1 \cancel{\text{mol}}}$$

$$m_{H_2O} = 0.727 \text{ g}$$

The mass of water required would be 0.727 g.

Applying Inquiry Skills

13. (a) **Prediction**

The molar volume of oxygen at STP will be 22.4 L/mol, just as for any other gas, according to Avogadro's theory.

(b) **Analysis**

m_{O_2} = (46.84 – 45.79) g = 1.05 g

p_1 = (95.2 – 2.64) kPa = 92.6 kPa

v_1 = 848 mL

T_1 = 22°C = 295 K

p_2 = 101.325 kPa

v_{O_2} = ?

T_2 = 0°C = 273 K

M_{O_2} = 32.00 g/mol

V_{STP} = ?

$$n_{O_2} = 1.05 \cancel{\text{g}} \times \frac{1 \text{ mol}}{32.00 \cancel{\text{g}}}$$

$$n_{O_2} = 0.0328 \text{ mol} = 32.8 \text{ mmol}$$

$$\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2}$$

$$v_{O_2} = \frac{T_2 p_1 v_1}{T_1 p_2}$$

$$= \frac{273 \cancel{\text{K}} \times 92.6 \cancel{\text{kPa}} \times 848 \text{ mL}}{295 \cancel{\text{K}} \times 101.325 \cancel{\text{kPa}}}$$

$$v_{O_2} = 717 \text{ mL}$$

or

$$v_{O_2} = 848 \text{ mL} \times \frac{92.6 \cancel{\text{kPa}}}{101.325 \cancel{\text{kPa}}} \times \frac{273 \cancel{\text{K}}}{295 \cancel{\text{K}}}$$

$$v_{O_2} = 717 \text{ mL}$$

The volume of oxygen at STP would be 717 mL. Since this is an amount of 32.8 mmol, the molar volume can now be calculated as follows:

$$V_{STP} = \frac{717\ \cancel{m}L}{32.8\ \cancel{m}mol}$$

$$V_{STP} = 21.9\ L/mol$$

According to the evidence from this investigation, the molar volume of oxygen at STP is 21.9 L/mol.

(c) **Evaluation**

The prediction is judged to be verified, because the value calculated from the evidence is in close agreement.

$$\text{difference} = |22.4 - 21.9|\ L/mol = 0.5\ L/mol$$

$$\%\ \text{difference} = \frac{0.5\ L/\cancel{mol}}{22.4\ L/\cancel{mol}} \times 100\% = 2\%$$

(d) **Evaluation**

Avogadro's theory is supported by the result of this investigation, because the result agrees well with the prediction made from this authority.

Making Connections

14. (a) $M_{CO_2} = 44.10\ g/mol$

$V_{SATP} = 24.8\ L/mol$

$\text{density}_{CO_2} = ?$

$$\text{density}_{CO_2} = \frac{44.10\ g/\cancel{mol}}{24.8\ L/\cancel{mol}}$$

$\text{density}_{CO_2} = 1.8\ g/L$ (to 2 significant digits)

The density of carbon dioxide at SATP is 1.8 g/L.

(b) Carbon dioxide is denser than air, and so will stay near the base of a fire to displace oxygen to extinguish the fire.

(c) Carbon dioxide also works as an extinguisher because it will not support combustion.

SECTION 10.2 QUESTIONS

(Page 474)

Understanding Concepts

1. (a) Avogadro's theory states that equal volumes of gases at equal temperature and pressure have equal numbers of particles.

   (b) Avogadro's theory provides the concept of a molar volume for substances in the gas phase, allowing chemical calculations to be made easily for reactions with components that are gaseous.

2. $4\ NH_{3(g)} + 5\ O_{2(g)} \rightarrow 4\ NO_{(g)} + 6\ H_2O_{(g)}$

$4\ NH_{3(g)}$	+	$5\ O_{2(g)}$	$\rightarrow$	$4\ NO_{(g)}$	+	$6\ H_2O_{(g)}$
100 L		v		v		v

All gases measured at 800°C and 200 kPa.

$$v_{O_2} = 100\ L \times \frac{5}{4}$$

$$v_{O_2} = 125\ L$$

or

$$v_{O_2} = 100\ \cancel{L}\ \cancel{NH_3} \times \frac{5\ L\ O_2}{4\ \cancel{L}\ \cancel{NH_3}}$$

$$v_{O_2} = 125\ L$$

The volume of oxygen required is 125 L.

$$v_{NO} = 100\text{ L} \times \frac{4}{4}$$
$$v_{NO} = 100\text{ L}$$

or

$$v_{NO} = 100\ \cancel{\text{L}}\ \cancel{\text{NH}_3} \times \frac{4\text{ L NO}}{4\ \cancel{\text{L}}\ \cancel{\text{NH}_3}}$$
$$v_{NO} = 100\text{ L}$$

The volume of nitrogen oxide produced is 100 L.

$$v_{H_2O} = 100\text{ L} \times \frac{6}{4}$$
$$v_{H_2O} = 150\text{ L}$$

or

$$v_{H_2O} = 100\ \cancel{\text{L}}\ \cancel{\text{NH}_3} \times \frac{6\text{ L H}_2\text{O}}{4\ \cancel{\text{L}}\ \cancel{\text{NH}_3}}$$
$$v_{H_2O} = 150\text{ L}$$

The volume of water vapour produced is 150 L.

(b) $2\ NO_{(g)} + O_{2(g)} \rightarrow 2\ NO_{2(g)}$

	v	750 L

All gases measured at 800°C and 200 kPa.

$$v_{O_2} = 750\text{ L} \times \frac{1}{2}$$
$$v_{O_2} = 375\text{ L}$$

or

$$v_{O_2} = 750\ \cancel{\text{L}}\ \cancel{\text{NO}_2} \times \frac{1\text{ L O}_2}{2\ \cancel{\text{L}}\ \cancel{\text{NO}_2}}$$
$$v_{O_2} = 375\text{ L}$$

The volume of oxygen required is 375 L.

(c) $3\ NO_{2(g)} + H_2O_{(l)} \rightarrow 2\ HNO_{3(aq)} + NO_{(g)}$

100 L		v

All gases measured at the same temperature and pressure.

$$v_{NO} = 100\text{ L} \times \frac{1}{3}$$
$$v_{NO} = 33.3\text{ L}$$

or

$$v_{NO} = 100\ \cancel{\text{L}}\ \cancel{\text{NO}_2} \times \frac{1\text{ L NO}}{3\ \cancel{\text{L}}\ \cancel{\text{NO}_2}}$$
$$v_{NO} = 33.3\text{ L}$$

The volume of nitrogen monoxide produced is 33.3 L.

(d) No prediction can be made from the law of combining volumes, because the nitric acid and the ammonium nitrate are in aqueous solution, not in gaseous form.

3. (a) $n_{H_2} = 7.50\text{ mol}$

$v_{H_2} = ?$

$V_{SATP} = 24.8\text{ L/mol}$

$$v_{H_2} = 7.50\ \cancel{\text{mol}} \times \frac{24.8\text{ L}}{1\ \cancel{\text{mol}}}$$
$$v_{H_2} = 186\text{ L}$$

The volume occupied by the hydrogen is 186 L.

(b) $p_1 = 100 \text{ kPa}$

$T_1 = 25^\circ\text{C} = 298 \text{ K}$

$v_1 = 186 \text{ L}$

$p_2 = 1.2 \text{ kPa}$

$T_2 = –47^\circ\text{C} = 226 \text{ K}$

$v_{H_2} = ?$

$$\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2}$$

$$v_{H_2} = \frac{T_2 p_1 v_1}{T_1 p_2}$$

$$= \frac{226 \cancel{\text{K}} \times 100 \cancel{\text{kPa}} \times 186 \text{ L}}{298 \cancel{\text{K}} \times 1.2 \cancel{\text{kPa}}}$$

$$v_{H_2} = 1.8 \times 10^4 \text{ L} = 18 \text{ kL}$$

or

$$v_{H_2} = 186 \text{ L} \times \frac{100 \cancel{\text{kPa}}}{1.2 \cancel{\text{kPa}}} \times \frac{226 \cancel{\text{K}}}{298 \cancel{\text{K}}}$$

$$v_{H_2} = 1.8 \times 10^4 \text{ L} = 18 \text{ kL}$$

The final volume of hydrogen in the balloon will be 18 kL.

4. v_{O_2} = 20% of 20.0 L = 4.0 L

$V_{STP} = 22.4 \text{ L/mol}$

$n_{O_2} = ?$

$$n_{O_2} = 4.0 \cancel{\text{L}} \times \frac{1 \text{ mol}}{22.4 \cancel{\text{L}}}$$

$$n_{O_2} = 0.18 \text{ mol}$$

The amount of oxygen present is 0.18 mol.

5. $m_{CO_2} = 1.00 \text{ t} = 1.00 \text{ Mg}$

$V_{STP} = 22.4 \text{ L/mol}$

$M_{CO_2} = 44.01 \text{ g/mol}$

$v_{CO_2} = ?$

$$n_{CO_2} = 1.00 \text{ M}\cancel{\text{g}} \times \frac{1 \text{ mol}}{44.01 \cancel{\text{g}}}$$

$$n_{CO_2} = 0.0227 \text{ Mmol} = 22.7 \text{ kmol}$$

$$v_{CO_2} = 22.7 \text{ k}\cancel{\text{mol}} \times \frac{22.4 \text{ L}}{1 \cancel{\text{mol}}}$$

$$v_{CO_2} = 509 \text{ kL}$$

or

$$v_{CO_2} = 1.00 \text{ M}\cancel{\text{g}} \times \frac{1 \cancel{\text{mol}}}{44.01 \cancel{\text{g}}} \times \frac{22.4 \text{ L}}{1 \cancel{\text{mol}}}$$

$$v_{CO_2} = 0.509 \text{ ML} = 509 \text{ kL}$$

The volume of carbon dioxide at STP would be 509 kL, or 509 m^3.

6. $m_{O_2} = ?$

$v_{O_2} = 1.9 \text{ kL}$

V_{SATP} = 24.8 L/mol

M_{O_2} = 32.00 g/mol

$$n_{O_2} = 1.9\ \text{k}\cancel{\text{L}} \times \frac{1\ \text{mol}}{24.8\ \cancel{\text{L}}}$$

$$n_{O_2} = 0.077\ \text{kmol}$$

$$m_{O_2} = 0.077\ \text{k}\cancel{\text{mol}} \times \frac{32.00\ \text{g}}{1\ \cancel{\text{mol}}}$$

$$m_{O_2} = 2.5\ \text{kg}$$

or

$$m_{O_2} = 1.9\ \text{k}\cancel{\text{L}} \times \frac{1\ \cancel{\text{mol}}}{24.8\ \cancel{\text{L}}} \times \frac{32.00\ \text{g}}{1\ \cancel{\text{mol}}}$$

$$m_{O_2} = 2.5\ \text{kg}$$

The mass of oxygen consumed would be 2.5 kg.

10.3 THE OZONE LAYER

PRACTICE

(Page 479)

Understanding Concepts

1. Ozone intercepts mostly the highest-energy (shorter wavelength) UV radiation from the Sun. Some UV radiation is absorbed by oxygen to become ozone, and some UV radiation is absorbed by ozone decomposing.
2. CFCs were developed as stable, non-toxic refrigerants, aerosol propellants, and foaming agents.
3. In the upper stratosphere, CFCs initiate reactions that increase the rate of decomposition of ozone.
4. An ozone "hole" is a (misleading) name for a region of very low ozone concentration; it is not a region where there is no ozone.
5.

$$CF_3 \overset{uv}{+} Br_{(g)} \rightarrow CFBr_{2(g)} + Br_{(g)}$$

$$Br_{(g)} + O_{3(g)} \rightarrow BrO_{(g)} + O_{2(g)}$$

$$BrO_{(g)} + O_{(g)} \rightarrow Br_{(g)} + O_{2(g)}$$

6. Ozone depletion is less severe in the Arctic because it is not as cold as the Antarctic, and because there is more air mixing due to prevailing winds.
7. Suntanning time should be decreased proportionally to a drop in the level of ozone in the stratosphere. Current medical thinking is that there is no absolutely "safe" level of sunlight exposure; so the perceived benefits of outdoor activities — and particularly of deliberate tanning — must be weighed against the increased risks of skin damage and skin cancer.

SECTION 10.3 QUESTIONS

(Page 480)

Understanding Concepts

1. The Montreal Protocol is an agreement among nations to decrease the production and use of CFCs, to try to prevent damage to stratospheric ozone.
2. Freeon-12 is a CFC refrigerant that is routinely recycled.
3. HFE can replace CFCs for many uses, and hydrocarbons can be used as refrigerants.
4. Canada's Arctic Observatory and National Research Council contribute to research on effects of CFCs and the development of alternative substances.
5. Stratospheric ozone helps us by filtering potentially harmful UV radiation; but at low levels of the atmosphere (in the air we breathe) ozone is dangerous — a very reactive and toxic substance.