Name ________________________________ Date ________ Class ______________________

CHEMFILE MINI-GUIDE TO PROBLEM SOLVING

Stoichiometry of Gases

Now that you have worked with relationships among moles, mass, and volumes of gases, you can easily put these to work in stoichiometry calculations. Many reactions have gaseous reactants, gaseous products, or both.

Reactants and products that are not gases are usually measured in grams or kilograms. As you know, you must convert these masses to amounts in moles before you can relate the quantities by using a balanced chemical equation. Gaseous products and reactants can be related to solid or liquid products and reactants by using the mole ratio, just as solids and liquids are related to each other.

Reactants and products that are gases are usually measured in liters. If the gas is measured at STP, you will need only Avogadro's law to relate the volume and amount of a gas. One mole of any gas at STP occupies 22.4 L. If the gas is not at STP, you will need to use the ideal gas law to determine the number of moles. Once volume has been converted to amount in moles you can use the mole ratios of products and reactants to solve stoichiometry problems involving multiple phases of products and reactants.

$$n = \frac{PV}{RT}$$

If the problem which you are trying to solve involves only gases, there is a simpler way of dealing with the stoichiometric amounts. Look again at the expression for the ideal gas law above; the molar amount of a gas is directly related to its volume. Therefore, the mole ratios of gases given by the coefficients in the balanced equation can be used as volume ratios of those gases to solve stoichiometry problems. No conversion from volume to amount is required to determine the volume of one gas from the volume of another gas in a balanced chemical equation.

There is one condition that must be observed. Gas volumes can be related by mole ratios only when the volumes are measured under the same conditions of temperature and pressure. If they are not, then the volume of one of the gases must be converted to the conditions of the other gas. Usually you will need to use the combined gas law for this conversion.

$$V_2 = \frac{V_1P_1T_2}{T_1P_2}$$

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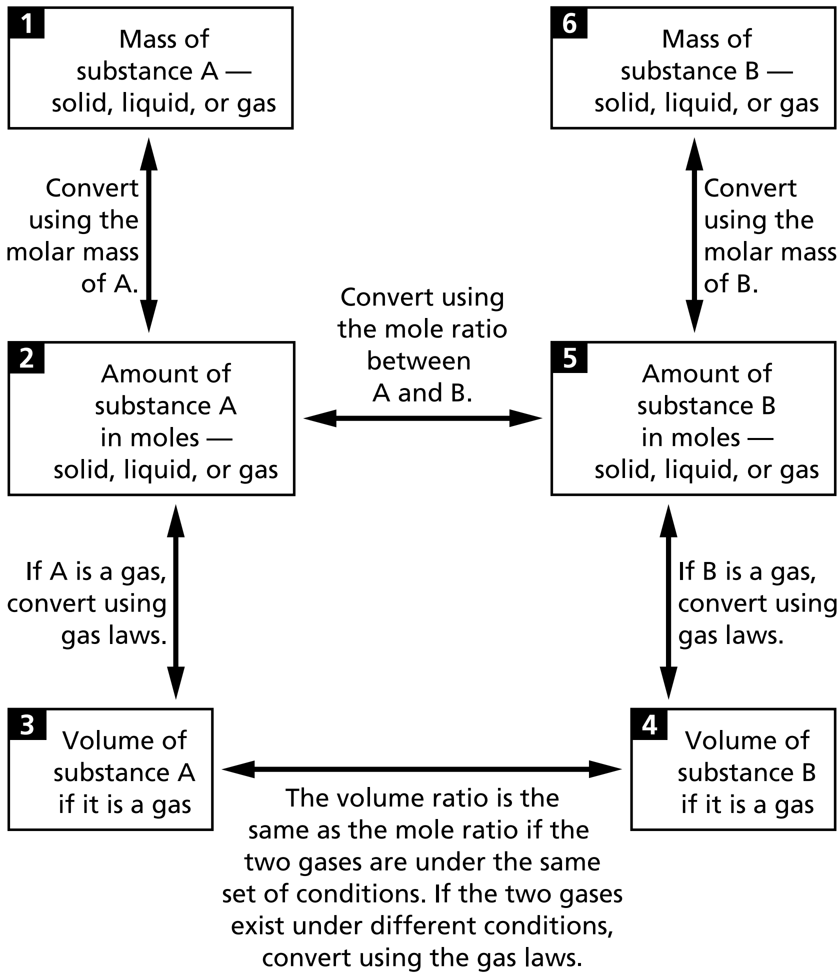
General Plan for Solving Gas Stoichiometry Problems



SAMPLE PROBLEM 1

Ammonia can react with oxygen to produce nitrogen and water according to the following equation.

$$4NH_3(g) + 3O_2(g) \rightarrow 2N_2(g) + 6H_2O(l)$$

If 1.78 L of O_2 reacts, what volume of nitrogen will be produced? Assume that temperature and pressure remain constant.

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SOLUTION

1. *ANALYZE*

- *What is given in the problem?* — the balanced equation, the volume of oxygen, and the fact that the two gases exist under the same conditions
- *What are you asked to find?* — the volume of N_2 produced

Items	Data	
Substance	O_2	N_2
Coefficient in balanced equation	3	2
Molar mass	NA	NA
Moles	NA	NA
Mass of substance	NA	NA
Volume of substance	1.78 L	? L
Temperature conditions	NA	NA
Pressure conditions	NA	NA

2. *PLAN*

- *What steps are needed to calculate the volume of N_2 formed from a given volume of O_2?* — The coefficients of the balanced equation indicate the mole ratio of O_2 to N_2. The volume ratio is the same as the mole ratio when volumes are measured under the same conditions.

3 Volume of O_2 in L → *multiply by the volume ratio,* $\frac{N_2}{O_2}$ → **4** Volume of N_2 in L

$$\overset{given}{L\ O_2} \times \overset{\text{volume ratio, } \frac{N_2}{O_2}}{\frac{2\ L\ N_2}{3\ L\ O_2}} = L\ N_2$$

3. *COMPUTE*

$$1.78\ \cancel{L\ O_2} \times \frac{2\ L\ N_2}{3\ \cancel{L\ O_2}} = 1.19\ L\ N_2$$

4. *EVALUATE*

- *Are the units correct?* — Yes; units canceled to give L N_2.

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- *Is the number of significant figures correct?* — Yes; the number of significant figures is correct because the data were given to three significant figures.
- *Is the answer reasonable?* — Yes; the volume of N_2 should be 2/3 the volume of O_2.

PRACTICE

1. In one method of manufacturing nitric acid, ammonia is oxidized to nitrogen monoxide and water.

$$4NH_3(g) + 5O_2(g) \rightarrow 4NO(g) + 6H_2O(l)$$

What volume of oxygen will be used in a reaction of 2800 L of NH_3? What volume of NO will be produced? All volumes are measured under the same conditions.

ans: 3500 L O_2
2800 L NO

2. Fluorine gas reacts violently with water to produce hydrogen fluoride and ozone according to the following equation.

$$3F_2(g) + 3H_2O(l) \rightarrow 6HF(g) + O_3(g)$$

What volumes of O_3 and HF gas would be produced by the complete reaction of 3.60×10^4 mL of fluorine gas? All gases are measured under the same conditions.

ans: 1.20×10^4 mL O_3
7.20×10^4 mL HF

SAMPLE PROBLEM 2

Ethylene gas burns in air according to the following equation.

$$C_2H_4(g) + 3O_2(g) \rightarrow 2CO_2(g) + 2H_2O(l)$$

If 13.8 L of C_2H_4 measured at 21°C and 1.038 atm burns completely with oxygen, calculate the volume of CO_2 produced, assuming the CO_2 is measured at 44°C and 0.989 atm.

SOLUTION

1. *ANALYZE*

- *What is given in the problem?* — the balanced equation, the volume of ethylene, the conditions under which the ethylene was measured, and the conditions under which the CO_2 is measured

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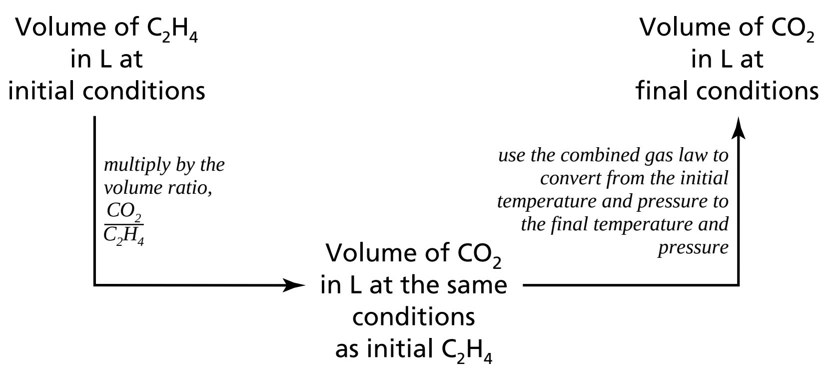
- *What are you asked to find?* — the volume of CO_2 produced as measured at the specified conditions

Items	Data	
Substance	C_2H_4	CO_2
Coefficient in balanced equation	1	2
Molar mass	NA	NA
Moles	NA	NA
Mass of substance	NA	NA
Volume of substance	13.8 L	? L
Temperature conditions	21°C = 294 K	44°C = 317 K
Pressure conditions	1.083 atm	0.989 atm

2. *PLAN*

- *What steps are needed to calculate the volume of CO_2 formed from the complete burning of a given volume of C_2H_4?* — Use the volume ratio of C_2H_4 to CO_2 to calculate the volume of CO_2 at the same conditions as C_2H_4. Convert to the volume of CO_2 for the given conditions using the combined gas law.



$$\underset{}{\overset{\textit{given}}{\text{L } C_2H_4}}{}^{*} \times \overset{\textit{volume ratio, } \frac{CO_2}{C_2H_4}}{\frac{2 \text{ L } CO_2}{1 \text{ L } C_2H_4}} = \text{L } CO_2{}^{*}$$

* at 294 K and 1.083 atm

Neither pressure nor temperature is constant; therefore, the combined gas law must be used to calculate the volume of CO_2 at the final temperature and pressure.

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Name ________________________ Date ________ Class ________________

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

$$\frac{\underset{\text{given}}{T_2} \times \underset{\text{given}}{P_1} \times \underset{\text{calculated above}}{V_1}}{\underset{\text{given}}{P_2} \times \underset{\text{given}}{T_1}} = V_2$$

3. *COMPUTE*

$$13.8 \text{ L } \cancel{C_2H_4}^* \times \frac{2 \text{ L } CO_2}{1 \text{ L } \cancel{C_2H_4}} = 27.6 \text{ L } CO_2^*$$

* at 294 K and 1.083 atm

Solve the combined-gas-law equation for V_2.

$$V_2 = \frac{317 \cancel{\text{K}} \times 1.083 \cancel{\text{atm}} \times 27.6 \text{ L } CO_2}{0.989 \cancel{\text{atm}} \times 294 \cancel{\text{K}}} = 32.6 \text{ L } CO_2$$

4. *EVALUATE*

- *Are the units correct?* — Yes; units canceled to give L CO_2.
- *Is the number of significant figures correct?* — Yes; the number of significant figures is correct because the data had a minimum of three significant figures.
- *Is the answer reasonable?* — Yes; the changes in both pressure and temperature increased the volume by small factors.

PRACTICE

1. A sample of ethanol burns in O_2 to form CO_2 and H_2O according to the following equation.

$$C_2H_5OH + 3O_2 \rightarrow 2CO_2 + 3H_2O$$

If the combustion uses 55.8 mL of oxygen measured at 2.26 atm and 40.°C, what volume of CO_2 is produced when measured at STP? *ans:* 73.3 mL CO_2

2. Dinitrogen pentoxide decomposes into nitrogen dioxide and oxygen. If 5.00 L of N_2O_5 reacts at STP, what volume of NO_2 is produced when measured at 64.5°C and 1.76 atm? *ans:* 7.02 atm

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SAMPLE PROBLEM 3

When arsenic(III) sulfide is roasted in air, it reacts with oxygen to produce arsenic(III) oxide and sulfur dioxide according to the following equation.

$$2As_2S_3(s) + 9O_2(g) \rightarrow 2As_2O_3(s) + 6SO_2(g)$$

When 89.5 g of As_2S_3 is roasted with excess oxygen, what volume of SO_2 is produced? The gaseous product is measured at 20°C and 98.0 kPa.

SOLUTION

1. *ANALYZE*

- *What is given in the problem?* — the balanced equation, the mass of As_2S_3, and the pressure and temperature conditions under which the SO_2 is measured
- *What are you asked to find?* — the volume of SO_2 produced as measured at the given conditions

Items	**Data**	
Substance	$As_2S_3(s)$	$SO_2(g)$
Coefficient in balanced equation	2	6
Molar mass*	246.05 g/mol	NA
Mass of substance	89.5 g	NA
Amount	**?** mol	**?** mol
Volume of substance	NA	**?** L
Temperature conditions	NA	20°C = 293 K
Pressure conditions	NA	98.0 kPa

* determined from the periodic table

2. *PLAN*

- *What steps are needed to calculate the volume of SO_2 formed from the reaction of a given mass of As_2S_3?* — Use the molar mass of As_2S_3 to determine the number of moles that react. Use the mole ratio from the balanced chemical equation to determine the amount in moles of SO_2 formed. Use the ideal-gas-law equation to determine the volume of SO_2 formed from the amount in moles.

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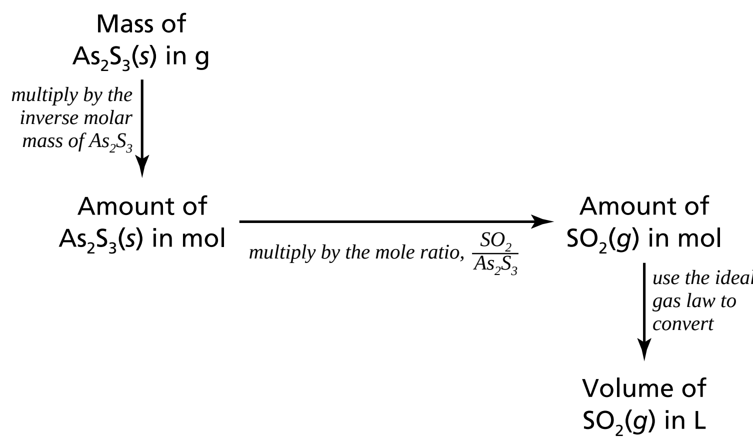

$$\underset{\text{given}}{\text{g } As_2S_3} \times \overset{\frac{1}{\text{molar mass } As_2S_3}}{\frac{1 \text{ mol } As_2S_3}{246.05 \text{ g } As_2S_3}} \times \overset{\text{mole ratio, } \frac{SO_2}{As_2S_3}}{\frac{6 \text{ mol } SO_2}{2 \text{ mol } As_2S_3}} = \text{mol } SO_2$$

Rearrange the ideal-gas-law equation to solve for the unknown quantity, *V*.

$$PV = nRT$$

$$V = \frac{nRT}{P}$$

$$\frac{\overset{\text{calculated above}}{\text{mol } SO_2} \times \overset{\text{ideal gas constant}}{8.314 \text{ L} \cdot \text{kPa/mol} \cdot \text{K}} \times \overset{\text{given}}{\text{K}}}{\underset{\text{given}}{\text{kPa}}} = \text{L } SO_2$$

3. *COMPUTE*

$$89.5 \cancel{\text{g } As_2S_3} \times \frac{1 \cancel{\text{mol } As_2S_3}}{246.05 \cancel{\text{g } As_2S_3}} \times \frac{6 \text{ mol } SO_2}{2 \cancel{\text{mol } As_2S_3}} = 1.09 \text{ mol } SO_2$$

$$\frac{1.09 \cancel{\text{mol}} \text{ } SO_2 \times 8.314 \text{ L} \cdot \cancel{\text{kPa}}/\cancel{\text{mol} \cdot \text{K}} \times 293 \cancel{\text{K}}}{98.0 \cancel{\text{kPa}}} = 27.1 \text{ L } SO_2$$

4. *EVALUATE*

- *Are the units correct?* Yes; units canceled to give liters of SO_2.
- *Is the number of significant figures correct?* Yes; the number of significant figures is correct because the data had a minimum of three significant figures.

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- *Is the answer reasonable?* Yes; computation of the amount of SO_2 can be approximated as $(9/25) \times 3 = 27/25$, so you would expect an answer a little greater than 1. At a temperature slightly above standard temperature, you would expect a volume a little greater than 22.4 L.

PRACTICE

1. Complete the table below using the following equation, which represents a reaction that produces aluminum chloride.

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

	Mass Al	Volume Cl_2	Conditions	Mass $AlCl_3$	
a.	excess	**?** L	STP	7.15 g	*ans:* 1.80 L Cl_2
b.	19.4 g	**?** L	STP	NA	*ans:* 24.2 L Cl_2
c.	1.559 kg	**?** L	20.°C and 0.945 atm	NA	*ans:* 2.21×10^3 L Cl_2
d.	excess	920. L	STP	**?** g	*ans:* 3.65×10^3 g $AlCl_3$
e.	**?** g	1.049 mL	37°C and 5.00 atm	NA	*ans:* 3.71×10^{-3} g Al
f.	500.00 kg	**?** m^3	15°C and 83.0 kPa	NA	*ans:* 8.02×10^2 m^3 Cl_2

ADDITIONAL PROBLEMS

1. The industrial production of ammonia proceeds according to the following equation.

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

a. What volume of nitrogen at STP is needed to react with 57.0 mL of hydrogen measured at STP?

b. What volume of NH_3 at STP can be produced from the complete reaction of 6.39×10^4 L of hydrogen?

c. If 20.0 mol of nitrogen is available, what volume of NH_3 at STP can be produced?

d. What volume of H_2 at STP will be needed to produce 800. L of ammonia, measured at 55°C and 0.900 atm?

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Name ______________________ Date ________ Class ______________

2. Propane burns according to the following equation.

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

a. What volume of water vapor measured at 250.°C and 1.00 atm is produced when 3.0 L of propane at STP is burned?

b. What volume of oxygen at 20.°C and 102.6 kPa is used if 640. L of CO_2 is produced? The CO_2 is also measured at 20.°C and 102.6 kPa.

c. If 465 mL of oxygen at STP is used in the reaction, what volume of CO_2, measured at 37°C and 0.973 atm, is produced?

d. When 2.50 L of C_3H_8 at STP burns, what total volume of gaseous products is formed? The volume of the products is measured at 175°C and 1.14 atm.

3. Carbon monoxide will burn in air to produce CO_2 according to the following equation.

$$2CO(g) + O_2(g) \rightarrow 2CO_2(g)$$

What volume of oxygen at STP will be needed to react with 3500. L of CO measured at 20.°C and a pressure of 0.953 atm?

4. Silicon tetrafluoride gas can be produced by the action of HF on silica according to the following equation.

$$SiO_2(s) + 4HF(g) \rightarrow SiF_4(g) + 2H_2O(l)$$

1.00 L of HF gas under pressure at 3.48 atm and a temperature of 25°C reacts completely with SiO_2 to form SiF_4. What volume of SiF_4, measured at 15°C and 0.940 atm, is produced by this reaction?

5. One method used in the eighteenth century to generate hydrogen was to pass steam through red-hot steel tubes. The following reaction takes place.

$$3Fe(s) + 4H_2O(g) \rightarrow Fe_3O_4(s) + 4H_2(g)$$

a. What volume of hydrogen at STP can be produced by the reaction of 6.28 g of iron?

b. What mass of iron will react with 500. L of steam at 250.°C and 1.00 atm pressure?

c. If 285 g of Fe_3O_4 are formed, what volume of hydrogen, measured at 20.°C and 1.06 atm, is produced?

6. Sodium reacts vigorously with water to produce hydrogen and sodium hydroxide according to the following equation.

$$2Na(s) + 2H_2O(l) \rightarrow 2NaOH(aq) + H_2(g)$$

If 0.027 g of sodium reacts with excess water, what volume of hydrogen at STP is formed?

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Name ______________________ Date ________ Class ________________

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7. Diethyl ether burns in air according to the following equation.

$$C_4H_{10}O(l) + 6O_2(g) \rightarrow 4CO_2(g) + 5H_2O(l)$$

If 7.15 L of CO_2 is produced at a temperature of 125°C and a pressure of 1.02 atm, what volume of oxygen, measured at STP, was consumed and what mass of diethyl ether was burned?

8. When nitroglycerin detonates, it produces large volumes of hot gases almost instantly according to the following equation.

$$4C_3H_5N_3O_9(l) \rightarrow 6N_2(g) + 12CO_2(g) + 10H_2O(g) + O_2(g)$$

a. When 0.100 mol of nitroglycerin explodes, what volume of each gas measured at STP is produced?

b. What total volume of gases is produced at 300.°C and 1.00 atm when 10.0 g of nitroglycerin explodes?

9. Dinitrogen monoxide can be prepared by heating ammonium nitrate, which decomposes according to the following equation.

$$NH_4NO_3(s) \rightarrow N_2O(g) + 2H_2O(l)$$

What mass of ammonium nitrate should be decomposed in order to produce 250. mL of N_2O, measured at STP?

10. Phosphine, PH_3, is the phosphorus analogue to ammonia, NH_3. It can be produced by the reaction between calcium phosphide and water according to the following equation.

$$Ca_3P_2(s) + 6H_2O(l) \rightarrow 3Ca(OH)_2(s \text{ and } aq) + 2PH_3(g)$$

What volume of phosphine, measured at 18°C and 102.4 kPa, is produced by the reaction of 8.46 g of Ca_3P_2?

11. In one method of producing aluminum chloride, HCl gas is passed over aluminum and the following reaction takes place.

$$2Al(s) + 6HCl(g) \rightarrow 2AlCl_3(g) + 3H_2(g)$$

What mass of Al should be on hand in order to produce 6.0×10^3 kg of $AlCl_3$? What volume of compressed HCl at 4.71 atm and a temperature of 43°C should be on hand at the same time?

12. Urea, $(NH_2)_2CO$, is an important fertilizer that is manufactured by the following reaction.

$$2NH_3(g) + CO_2(g) \rightarrow (NH_2)_2CO(s) + H_2O(g)$$

What volume of NH_3 at STP will be needed to produce 8.50×10^4 kg of urea if there is an 89.5% yield in the process?

13. An obsolete method of generating oxygen in the laboratory involves the decomposition of barium peroxide by the following equation.

$$2BaO_2(s) \rightarrow 2BaO(s) + O_2(g)$$

What mass of BaO_2 reacted if 265 mL of O_2 is collected by water displacement at 0.975 atm and 10.°C?

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14. It is possible to generate chlorine gas by dripping concentrated HCl solution onto solid potassium permanganate according to the following equation.

$$2KMnO_4(aq) + 16HCl(aq) \rightarrow 2KCl(aq) + 2MnCl_2(aq) + 8H_2O(l) + 5Cl_2(g)$$

If excess HCl is dripped onto 15.0 g of $KMnO_4$, what volume of Cl_2 will be produced? The Cl_2 is measured at 15°C and 0.959 atm.

15. Ammonia can be oxidized in the presence of a platinum catalyst according to the following equation.

$$4NH_3(g) + 5O_2(g) \rightarrow 4NO(g) + 6H_2O(l)$$

The NO that is produced reacts almost immediately with additional oxygen according to the following equation.

$$2NO(g) + O_2(g) \rightarrow 2NO_2(g)$$

If 35.0 kL of oxygen at STP react in the first reaction, what volume of NH_3 at STP reacts with it? What volume of NO_2 at STP will be formed in the second reaction, assuming there is excess oxygen that was not used up in the first reaction?

16. Oxygen can be generated in the laboratory by heating potassium chlorate. The reaction is represented by the following equation.

$$2KClO_3(s) \rightarrow 2KCl(s) + 3O_2(g)$$

What mass of $KClO_3$ must be used in order to generate 5.00 L of O_2, measured at STP?

17. One of the reactions in the Solvay process is used to make sodium hydrogen carbonate. It occurs when carbon dioxide and ammonia are passed through concentrated salt brine. The following equation represents the reaction.

$$NaCl(aq) + H_2O(l) + CO_2(g) + NH_3(g) \rightarrow NaHCO_3(s) + NH_4Cl(aq)$$

a. What volume of NH_3 at 25°C and 1.00 atm pressure will be required if 38 000 L of CO_2, measured under the same conditions, react to form $NaHCO_3$?

b. What mass of $NaHCO_3$ can be formed when the gases in (a) react with NaCl?

c. If this reaction forms 46.0 kg of $NaHCO_3$, what volume of NH_3, measured at STP, reacted?

d. What volume of CO_2, compressed in a tank at 5.50 atm and a temperature of 42°C, will be needed to produce 100.00 kg of $NaHCO_3$?

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18. The combustion of butane is represented in the following equation.

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

a. If 4.74 g of butane react with excess oxygen, what volume of CO_2, measured at 150.°C and 1.14 atm, will be formed?

b. What volume of oxygen, measured at 0.980 atm and 75°C, will be consumed by the complete combustion of 0.500 g of butane?

c. A butane-fueled torch has a mass of 876.2 g. After burning for some time, the torch has a mass of 859.3 g. What volume of CO_2, at STP, was formed while the torch burned?

d. What mass of H_2O is produced when butane burns and produces 3720 L of CO_2, measured at 35°C and 0.993 atm pressure?

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