Calculations Involving Limiting Reagents

7.4

How do you make a bicycle? Obviously, many specific parts must be assembled. Bike manufacturers must keep careful watch over their inventory during the production process. They must ensure that they have a minimum quantity of each bicycle part available at all times. If they run out of one part, the manufacturing process stops. At the same time, it is too costly to maintain a large oversupply of parts.

Similarly, chemical manufacturers must maintain careful inventory of the reactants used in a chemical process. For example, the titanium used to make bicycle frames is relatively abundant as a natural ore (**Figure 1**). However, extracting pure titanium from the ore is complicated and costly. The final step in the process is

$$TiCl_4(g) + 2\,Mg(l) \rightarrow Ti(s) + 2\,MgCl_2(l)$$

Since titanium tetrachloride and magnesium are in a 1:2 ratio in the chemical equation, at least twice the amount of magnesium must be present to ensure that all the expensive titanium tetrachloride is used up to make titanium metal. In practice, a slight excess of magnesium is always present.

Figure 1 Titanium metal is exceptionally light and very strong, making it ideal for bicycle frames.

Limiting Reagent Problems Involving Amounts

If you are given the quantities of two different reactants, you first have to figure out which one is the limiting reagent. You can then use this amount to predict what amount of product will be produced.

Tutorial 1 Solving Limiting Reagent Problems Involving Amounts

To determine the amount of product in a limiting reagent problem, follow the strategy developed in Section 7.2. The only difference is that you must first determine the limiting reagent.

Sample Problem 1: Predicting the Amount of Product

Determine the amount of titanium metal produced when 2.8 mol of titanium(IV) chloride reacts with 5.4 mol of magnesium.

$$TiCl_4(g) + 2\,Mg(l) \rightarrow Ti(s) + 2\,MgCl_2(l)$$

Given: $n_{TiCl_4} = 2.8$ mol; $n_{Mg} = 5.4$ mol

Required: mass of titanium, m_{Ti}

Solution:

Step 1. Write a balanced equation listing given value(s) and required value(s).

$$TiCl_4(g) + 2\,Mg(l) \rightarrow Ti(s) + 2\,MgCl_2(l)$$

2.8 mol 5.4 mol m_{Ti}

Step 2. To determine the limiting reagent, first use the amount of one reactant to find the stoichiometric amount of the other. As you will see, it does not matter which reactant you start with. In this case, we will convert amount of titanium(IV) chloride to amount of magnesium.

$$n_{Mg} = 2.8\ \cancel{mol_{TiCl_4}} \times \frac{2\ mol_{Mg}}{1\ \cancel{mol_{TiCl_4}}}$$

$$n_{Mg} = 5.6\ mol$$

Therefore 5.6 mol of magnesium is required to react with 2.8 mol of titanium(IV) chloride. Only 5.4 mol of magnesium is actually present. This amount is less than what is required. Therefore, magnesium is the limiting reagent and titanium(IV) chloride is the excess reagent.

LEARNING TIP

An Alternative Strategy

There is another way to identify the limiting reagent. For the reaction $aA + bB =$ products, if

$$\left(\frac{a}{b}\right) < \left(\frac{n_A}{n_B}\right)$$

then A is in excess, but if

$$\left(\frac{a}{b}\right) > \left(\frac{n_A}{n_B}\right)$$

then A is the limiting reagent.

You would reach the same conclusion if you initially chose titanium(IV) chloride:

$$n_{TiCl_4} = 5.4\ \cancel{\text{mol}}_{\text{Mg}} \times \frac{1\ \text{mol}_{TiCl_4}}{2\ \cancel{\text{mol}}_{\text{Mg}}}$$

$$n_{TiCl_4} = 2.7\ \text{mol}$$

Since more than 2.7 mol of titanium(IV) chloride is present initially, titanium(IV) chloride is the excess reagent. Therefore, magnesium is the limiting reagent.

Once the limiting reagent is determined, the remainder of this problem is the same as the stoichiometry problems in the previous section.

Step 3. Use the amount of limiting reagent to find the amount of required substance.

$$n_{\text{Ti}} = 5.4\ \cancel{\text{mol}}_{\text{Mg}} \times \frac{1\ \text{mol}_{\text{Ti}}}{2\ \cancel{\text{mol}}_{\text{Mg}}}$$

$$n_{\text{Ti}} = 2.7\ \text{mol}$$

Statement: When 2.8 mol of titanium(IV) chloride is combined with 5.4 mol of magnesium, 2.7 mol of titanium will be produced.

Practice

SKILLS HANDBOOK A6

1. A nitric acid spill is neutralized by adding sodium hydrogen carbonate, $NaHCO_3(s)$:

   $HNO_3(aq) + NaHCO_3(s) \rightarrow H_2O(l) + CO_2(g) + NaNO_3(aq)$

   What amount of water is produced when 2.3 mol of nitric acid is combined with 2.0 mol of sodium hydrogen carbonate? T/I [ans: 2.0 mol]
2. Chlorine can be produced in the lab by reacting hydrochloric acid with manganese(IV) oxide:

   $4\ HCl(aq) + MnO_2(s) \rightarrow Cl_2(g) + 2\ H_2O(l) + MnCl_2(aq)$

   What amount of chlorine can be made from 5.2 mol of hydrochloric acid and 1.5 mol of manganese dioxide? T/I [ans: 1.3 mol]
3. Aluminum reacts vigorously with iodine in a synthesis reaction. T/I C
   (a) Write a balanced chemical equation for this reaction.
   (b) Predict the amount of product that can be made from 0.50 mol of aluminum and 0.60 mol of iodine. [ans: 0.40 mol]
4. Aluminum can be used to produce iron from iron(III) oxide. T/I C
   (a) Write a balanced chemical equation for this reaction.
   (b) What amount of iron is expected when 0.26 mol of aluminum is combined with 0.10 mol of iron(III) oxide? [ans: 0.20 mol]
   (c) What amount of the other product is expected? [ans: 0.10 mol Al_2O_3]

Investigation 7.4.1

Copper Collection Stoichiometry (p. 341)
You will use stoichiometry to identify which of two possible iron compounds is formed when copper(II) sulfate solution reacts with an excess of iron.

WEB LINK

There are many online videos available to help you learn how to solve limiting reagent problems involving masses. Some use strategies other than those outlined here.

GO TO NELSON SCIENCE

Limiting Reagent Problems Involving Masses

Once you have identified the limiting reagent, you can predict the mass of product using the strategy outlined in Section 7.2.

Tutorial 2 Solving Limiting Reagent Problems Involving Masses

To solve limiting reagent problems involving masses, follow the same strategy as for any other stoichiometry problem involving masses. The only difference is that you first determine which reactant is the limiting reagent, then use the mass of the limiting reagent to determine the masses of product(s).

Sample Problem 1: Predicting the Mass of Product

Methanol, CH_3OH, can be made using a synthesis reaction involving carbon monoxide and hydrogen:

$$CO(g) + 2\ H_2(g) \rightarrow CH_3OH(l)$$

What mass of methanol can be produced from 9.80 g of carbon monoxide and 1.30 g of hydrogen?

Given: $m_{CO} = 9.80$ g; $m_{H_2} = 1.30$ g

Required: mass methanol, m_{CH_3OH}

Solution:

Step 1. Write a balanced equation listing given value(s), required value(s), and corresponding molar masses.

$CO(g)$	+	$2\ H_2(g) \rightarrow CH_3OH(l)$
9.80 g		1.30 g
28.01 g/mol		2.02 g/mol

Step 2. Convert mass of given substance to amount of given substance.

$$n_{CO} = 9.80\ \cancel{g} \times \frac{1\ \text{mol}}{28.01\ \cancel{g}}$$

$$n_{CO} = 0.34988\ \text{mol}\ [2\ \text{extra digits carried}]$$

$$n_{H_2} = 1.30\ \cancel{g} \times \frac{1\ \text{mol}}{2.02\ \cancel{g}}$$

$$n_{H_2} = 0.64356\ \text{mol}\ [2\ \text{extra digits carried}]$$

Step 3. To determine the limiting reagent, first use the amount of one reactant to find the stoichiometric amount of the other.

$$n_{CO} = 0.64356\ \cancel{\text{mol}_{H_2}} \times \frac{1\ \text{mol}_{CO}}{2\ \cancel{\text{mol}_{H_2}}}$$

$$n_{CO} = 0.32178\ \text{mol}$$

0.32178 mol of carbon monoxide is required to completely react with the given amount of hydrogen. Since the amount of carbon monoxide present initially is greater than this amount, carbon monoxide is the excess reagent. Therefore, hydrogen must be the limiting reagent.

Step 4. Use the amount of the limiting reagent to find the amount of required substance.

$$n_{CH_3OH} = 0.64356\ \cancel{\text{mol}_{H_2}} \times \frac{1\ \text{mol}_{CH_3OH}}{2\ \cancel{\text{mol}_{H_2}}}$$

$$n_{CH_3OH} = 0.32178\ \text{mol}$$

Step 5. Convert amount of required substance to mass of required substance.

$$m_{CH_3OH} = (0.32178\ \cancel{\text{mol}})\left(\frac{32.02\ \text{g}}{1\ \cancel{\text{mol}}}\right)$$

$$m_{CH_3OH} = 10.3\ \text{g}$$

Statement: When 9.80 g of carbon monoxide reacts with 1.30 g of hydrogen, 10.3 g of methanol will be produced.

Figure 2 summarizes the strategy used to solve Sample Problem 1.

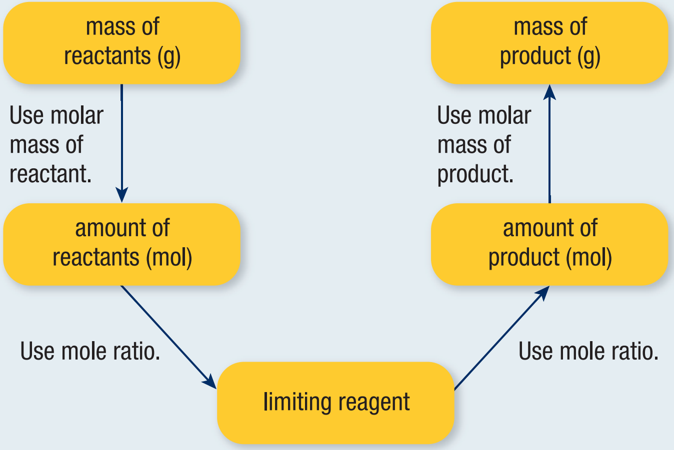

Figure 2 Strategy for solving limiting reagent problems

Alternatively, the calculation can be completed in one step, once the limiting reagent has been identified.

$$m_{CH_3OH} = \left(1.30\ g_{H_2} \times \frac{1\ mol_{H_2}}{2.02\ g_{H_2}}\right)\left(\frac{1\ mol_{CH_3OH}}{2\ mol_{H_2}}\right)\left(\frac{32.02\ g}{1\ mol_{CH_3OH}}\right)$$

$$m_{CH_3OH} = 10.3\ g$$

Practice

SKILLS HANDBOOK A6

1. Silicon carbide, SiC, also known as carborundum, is a hard, industrial abrasive used on grinding wheels to cut metal. Silicon carbide can be made by reacting silicon dioxide, SiO_2, with carbon at high temperatures:

   $SiO_2(s) + 3\ C(s) \rightarrow SiC(s) + 2\ CO_2(g)$

   Determine the mass of silicon carbide expected when 10.0 g of silicon dioxide is combined with 7.00 g of carbon. T/I [ans: 6.67 g]

2. Iron reacts with chlorine gas to form iron(III) chloride:

   $2\ Fe(s) + 3\ Cl_2(g) \rightarrow 2\ FeCl_3(s)$

   What mass of iron(III) chloride is expected if 5.00 g of iron is combined with 9.00 g of chlorine? T/I [ans: 13.7 g]

3. Ammonia, $NH_3(g)$, reacts with oxygen to form nitrogen monoxide, NO(g), and water:

   $4\ NH_3(g) + 5\ O_2(g) \rightarrow 4\ NO(g) + 6\ H_2O(g)$ T/I

   (a) Determine the limiting reagent if 0.34 g of ammonia combines with 1.00 g of oxygen.

   (b) What masses of nitrogen monoxide and water are produced in this reaction? [ans: 0.60 g NO; 0.54 g H_2O]

7.4 Summary

- In a limiting reagent problem, the amount of the limiting reagent determines the amount of product.
- The amount of product formed can only be predicted from the amount of the limiting reagent, not from the mass.
- Figure 2 outlines a strategy to solve limiting reagent problems.

7.4 Questions

1. Copy **Table 1** into your notebook and fill in the missing quantities. K/U T/I

Table 1 Amounts Involved in the Synthesis of Water

$2\ H_2(g)$ +	$O_2(g)$ →	$2\ H_2O(g)$	
Amount of hydrogen (mol)	Amount of oxygen (mol)	Amount of water (mol)	Amount of excess reagent remaining (mol)
2	2		
6	2		
0.4	0.8		
		5	3 mol H_2

2. Copy **Table 2** into your notebook and fill in the missing quantities. K/U T/I

Table 2 Amounts Involved in the Synthesis of Ammonia

$N_2(g)$ +	$3\ H_2(g)$ →	$2\ NH_3(g)$	
Amount of nitrogen (mol)	Amount of hydrogen (mol)	Amount of ammonia (mol)	Amount of excess reagent remaining (mol)
4	13		
0.90	0.25		
		0.16	0.22 mol N_2
		3.0	0.50 mol H_2
1.4			0.80 mol H_2

3. Determine the limiting and excess reagents for each of the following pairs of reactants: K/U T/I
   (a) 0.58 mol of magnesium and 0.20 mol of nitrogen:

   $3\ Mg(s) + N_2(g) \rightarrow Mg_3N_2(s)$

   (b) 5.3 mol of calcium and 3.8 mol of aluminum chloride:

   $3\ Ca(s) + 2\ AlCl_3(aq) \rightarrow 3\ CaCl_2(aq) + 2\ Al(s)$

   (c) 0.10 mol of iron pyrite, $FeS_2(s)$, and 0.35 mol of oxygen:

   $4\ FeS_2(s) + 11\ O_2(g) \rightarrow 2\ Fe_2O_3(s) + 8\ SO_2(g)$

4. Chemists can produce silver metal by reacting copper metal with a solution of silver nitrate:

   $Cu(s) + 2\ AgNO_3(aq) \rightarrow 2\ Ag(s) + Cu(NO_3)_2(aq)$ K/U T/I

   (a) Predict the amount of silver produced if 0.24 mol of copper were combined with 0.52 mol of silver nitrate.
   (b) Predict the amount of excess reagent remaining.

5. Aluminum chloride is an important industrial catalyst. It can be made by reacting aluminum metal with hydrochloric acid:

   $2\ Al(s) + 6\ HCl(aq) \rightarrow 2\ AlCl_3(aq) + 3\ H_2(g)$ K/U T/I

   (a) Predict the amount of aluminum chloride produced when 0.35 mol of aluminum is combined with 1.2 mol of hydrochloric acid.
   (b) Predict the amount of excess reagent remaining.

6. Determine the mass of sulfur trioxide produced when 5.8 mol of sulfur dioxide, SO_2, and 2.8 mol of oxygen combine to form sulfur trioxide (**Figure 3**):

   $2\ SO_2(g) + O_2(g) \rightarrow 2\ SO_3(g)$ T/I

Figure 3 On a typical day, the Kilauea volcano in Hawaii emits about 150 to 200 t of sulfur dioxide, most of which reacts to form sulfur trioxide.

7. Hydrogen reacts with chlorine to form gaseous hydrogen chloride. K/U T/I C
   (a) Write a balanced chemical equation for this reaction.
   (b) What mass of product is expected if 10.0 g of hydrogen mixes with 320.0 g of chlorine?

8. Aluminum hydroxide in antacid tablets neutralizes hydrochloric acid in the stomach:

   $Al(OH)_3(s) + 3\ HCl(aq) \rightarrow 3\ H_2O(l) + AlCl_3(aq)$

   If 0.50 g of aluminum hydroxide is placed in a solution containing 0.60 g of hydrochloric acid, predict what mass of aluminum chloride will form. T/I

9. The chemical equation for the combustion of butane is

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

   Predict what mass of carbon dioxide is produced from 10.0 g of butane and 30.0 g of oxygen. T/I

10. Titanium ore contains titanium(IV) oxide, TiO_2. During the production of titanium metal, this compound is first converted to titanium(IV) chloride:

    $TiO_2(s) + C(s) + 2\ Cl_2(g) \rightarrow TiCl_4(g) + CO_2(g)$ T/I

    (a) Identify the limiting reagent if 40.0 g of titanium(IV) oxide, 7.0 g of carbon, and 30.0 g of chlorine mix.
    (b) What mass of titanium(IV) chloride can be produced from these quantities?

11. Hydrogen cyanide, HCN(g), can be made in two steps:

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

    $2\ NO(g) + 2\ CH_4(g) \rightarrow 2\ HCN(g) + 2\ H_2O(g) + H_2(g)$

    If 15.0 g of ammonia, $NH_3(g)$, and 6.0 g of methane, $CH_4(g)$, are present initially with an excess of oxygen, predict what mass of hydrogen cyanide will be produced. T/I