5.6 THE YIELD OF A CHEMICAL REACTION

PRACTICE

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Understanding Concepts

1. The quantity of product predicted by stoichiometric calculation is the theoretical yield. When the reaction is carried out, the measured quantity of product obtained is the actual yield.
2. An actual yield is a measured quantity, and normal measurement error as well as experimental error can result in this value being greater than the theoretical yield.
3. (a) $NaBr_{(aq)} + AgNO_{3(aq)} \rightarrow NaNO_{3(aq)} + AgBr_{(s)}$

(b)

$NaBr_{(aq)}$	+	$AgNO_{3(aq)}$	$\rightarrow$	$NaNO_{3(aq)}$	+	$AgBr_{(s)}$
		5.00 g				m (5.03 g actual)
		169.88 g/mol				187.77 g/mol

$$n_{AgNO_3} = 5.00\ \cancel{g} \times \frac{1\ mol}{169.88\ \cancel{g}}$$
$$n_{AgNO_3} = 0.0294\ mol$$
$$n_{AgBr} = 0.0294\ mol \times \frac{1}{1}$$
$$n_{AgBr} = 0.0294\ mol$$
$$m_{AgBr} = 0.0294\ \cancel{mol} \times \frac{187.77\ g}{1\ \cancel{mol}}$$
$$m_{AgBr} = 5.53\ g$$

or

$$m_{AgBr} = 5.00\ \cancel{g}\ \cancel{AgNO_3} \times \frac{1\ \cancel{mol}\ \cancel{AgNO_3}}{169.88\ \cancel{g}\ \cancel{AgNO_3}} \times \frac{1\ \cancel{mol}\ \cancel{AgBr}}{1\ \cancel{mol}\ \cancel{AgNO_3}} \times \frac{187.77\ g\ AgBr}{1\ \cancel{mol}\ \cancel{AgBr}}$$
$$m_{AgBr} = 5.53\ g$$

The mass of silver bromide produced should be 5.53 g.

(c) The mass of silver bromide actually produced is 5.03 g.

(d) $$\%\ yield = \frac{actual\ yield}{theoretical\ yield} \times 100\%$$

$$\%\ yield = \frac{5.03\ \cancel{g}}{5.53\ \cancel{g}} \times 100\% = 91.0\%$$

The percentage yield of silver bromide in this reaction is 91.0%.

4. (a)

$4\ FeS_{(s)}$	+	$7\ O_{2(g)}$	$\rightarrow$	$2\ Fe_2O_{3(s)}$	+	$4\ SO_{2(g)}$
16.1 g		10.8 g				
87.91 g/mol		32.00 g/mol				

$$n_{FeS} = 16.1\ \cancel{g} \times \frac{1\ mol}{87.91\ \cancel{g}}$$
$$n_{FeS} = 0.183\ mol$$
$$n_{O_2} = 10.8\ \cancel{g} \times \frac{1\ mol}{32.00\ \cancel{g}}$$
$$n_{O_2} = 0.338\ mol$$

Since this reactant mole ratio is 4:7, 0.183 mol of $FeS_{(s)}$ will require 0.183 mol × 7/4 = 0.320 mol of $O_{2(g)}$ for reaction. The $O_{2(g)}$ is in excess; so the $FeS_{(s)}$ is the limiting reagent.

(b)

$4\ FeS_{(s)}$	+	$7\ O_{2(g)}$	$\rightarrow$	$2\ Fe_2O_{3(s)}$	+	$4\ SO_{2(g)}$
16.1 g				m (14.1 g actual)		
87.91 g/mol				159.70 g/mol		

$$n_{FeS} = 16.1\ \cancel{g} \times \frac{1\ mol}{87.91\ \cancel{g}}$$

n_{FeS} = 0.183 mol

$n_{Fe_2O_3}$ = $0.183 \text{ mol} \times \frac{2}{4}$

$n_{Fe_2O_3}$ = 0.0916 mol

$m_{Fe_2O_3}$ = $0.0916 \cancel{\text{mol}} \times \frac{159.70 \text{ g}}{1 \cancel{\text{mol}}}$

$m_{Fe_2O_3}$ = 14.6 g

or

$m_{Fe_2O_3}$ = $16.1 \cancel{\text{g FeS}} \times \frac{1 \cancel{\text{mol FeS}}}{87.91 \cancel{\text{g FeS}}} \times \frac{2 \cancel{\text{mol Fe}_2\text{O}_3}}{4 \cancel{\text{mol FeS}}} \times \frac{159.70 \text{ g Fe}_2\text{O}_3}{1 \cancel{\text{mol Fe}_2\text{O}_3}}$

$m_{Fe_2O_3}$ = 14.6 g

The theoretical yield of iron(III) oxide would be 14.6 g.

(c) $\% \text{ yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$

$\% \text{ yield} = \frac{14.1 \cancel{\text{g}}}{14.6 \cancel{\text{g}}} \times 100\% = 96.6\%$

The percentage yield of iron(III) oxide in this reaction is 96.6%.

5. $Fe_2O_{3(s)}$ + $3\ CO_{(g)}$ → $2\ Fe_{(s)}$ + $3\ CO_{2(g)}$

1000 kg		m (635 kg actual)	
159.70 g/mol		55.85 g/mol	

$n_{Fe_2O_3}$ = $1000 \text{ k}\cancel{\text{g}} \times \frac{1 \text{ mol}}{159.70 \cancel{\text{g}}}$

$n_{Fe_2O_3}$ = 6.26 kmol

n_{Fe} = $6.26 \text{ kmol} \times \frac{2}{1}$

n_{Fe} = 12.5 kmol

m_{Fe} = $12.5 \text{ k}\cancel{\text{mol}} \times \frac{55.85 \text{ g}}{1 \cancel{\text{mol}}}$

m_{Fe} = 699 kg

or

m_{Fe} = $1000 \text{ k}\cancel{\text{g Fe}_2\text{O}_3} \times \frac{1 \cancel{\text{mol Fe}_2\text{O}_3}}{159.70 \cancel{\text{g Fe}_2\text{O}_3}} \times \frac{2 \cancel{\text{mol Fe}}}{1 \cancel{\text{mol Fe}_2\text{O}_3}} \times \frac{55.85 \text{ g Fe}}{1 \cancel{\text{mol Fe}}}$

m_{Fe} = 699 kg

% yield = $\frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$

% yield = $\frac{635 \text{ k}\cancel{\text{g}}}{699 \text{ k}\cancel{\text{g}}} \times 100\% = 90.8\%$

The percentage yield of iron in this reaction is 90.8%.

6. $C_7H_6O_{3(s)}$ + $CH_3OH_{(l)}$ → $C_8H_8O_{3(l)}$ + $H_2O_{(l)}$

2.00 g		m (1.65 g actual)	
138.13 g/mol		152.16 g/mol	

$n_{C_7H_6O_3}$ = $2.00 \cancel{\text{g}} \times \frac{1 \text{ mol}}{138.13 \cancel{\text{g}}}$

$n_{C_7H_6O_3}$ = 0.0145 mol

$n_{C_8H_8O_3}$ = $0.0145 \text{ mol} \times \frac{1}{1}$

$n_{C_8H_8O_3}$ = 0.0145 mol

$m_{C_8H_8O_3}$ = $0.0145 \cancel{\text{mol}} \times \frac{152.16 \text{ g}}{1 \cancel{\text{mol}}}$

$m_{C_8H_8O_3}$ = 2.20 g

or

$$m_{C_8H_8O_3} = 2.00\ \cancel{g}\ C_7H_6O_3 \times \frac{1\ \cancel{mol}\ \cancel{C_7H_6O_3}}{138.13\ \cancel{g}\ \cancel{C_7H_6O_3}} \times \frac{1\ \cancel{mol}\ \cancel{C_8H_8O_3}}{1\ \cancel{mol}\ \cancel{C_7H_6O_3}} \times \frac{152.16\ g\ C_8H_8O_3}{1\ \cancel{mol}\ \cancel{C_8H_8O_3}}$$

$$m_{C_8H_8O_3} = 2.20\ g$$

$$\%\ \text{yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$$

$$\%\ \text{yield} = \frac{1.65\ \cancel{g}}{2.20\ \cancel{g}} \times 100\% = 74.9\%.$$

The percentage yield of methyl salicylate in this reaction is 74.9%

Applying Inquiry Skills

7. The procedure listed is fatally flawed if the reaction produces any other product (besides the precipitate) that does not vaporize upon heating, because any such product will also be mixed with the precipitate in the evaporating dish. The normal way to efficiently recover a precipitate is to filter it using a piece of filter paper of known (measured) mass, wash and dry it, and measure the mass of the paper plus precipitate.

Making Connections

8. (a) Student research should indicate how large-scale industry practices and procedures result in a more efficient extraction of the red dye, carmine, from the bodies of female Dactylopus coccus insects (cochineal insects) than the original hand process of crushing the insects and simmering them in water to extract the dye. Since so many insects are needed to produce a reasonable amount (150 000 insects per kilogram of carmine), the product is costly and the process efficiency is, therefore, very important.
   (b) As the insects live on desert cactus plants, cochineal carmine can be produced in arid areas where no other profitable crop can be harvested. This means that in Peru a significantly profitable industry and source of income for the residents of desert areas depends on these tiny bugs.

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PRACTICE

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Understanding Concepts

9. Yield less than predicted in a reaction may be due to experimental error inherent in the procedure; to impurities in the reagents; to unwanted side reactions; and to reactions that are not quantitative — that do not "go to completion."

10. (a)

$2\ Cu_2O_{(s)}$ +	$Cu_2S_{(s)}$ →	$6\ Cu_{(s)}$ +	$SO_{2(g)}$
250 kg	129 kg		
143.10 g/mol	159.16 g/mol		

$$n_{Cu_2O} = 250\ k\cancel{g} \times \frac{1\ mol}{143.10\ \cancel{g}}$$

$$n_{Cu_2O} = 1.75\ kmol$$

$$n_{Cu_2S} = 129\ k\cancel{g} \times \frac{1\ mol}{159.16\ \cancel{g}}$$

$$n_{Cu_2S} = 0.811\ kmol$$

Since this reactant mole ratio is 2:1, 0.811 kmol of $Cu_2S_{(s)}$ will require 0.811 kmol × 2/1 = 1.62 kmol of $Cu_2O_{(s)}$ for reaction. The $Cu_2O_{(s)}$ is in excess; so the $Cu_2S_{(s)}$ is the limiting reagent.

(b)

$2\ Cu_2O_{(s)}$ +	$Cu_2S_{(s)}$ →	$6\ Cu_{(s)}$ +	$SO_{2(g)}$
	129 kg	m (285 kg actual)	
	159.16 g/mol	63.55 g/mol	

$$n_{Cu_2S} = 129\ k\cancel{g} \times \frac{1\ mol}{159.16\ \cancel{g}}$$

$$n_{Cu_2S} = 0.811\ kmol$$

$$n_{Cu} = 0.811 \text{ kmol} \times \frac{6}{1}$$

$$n_{Cu} = 4.86 \text{ kmol}$$

$$m_{Cu} = 4.86 \text{ k}\cancel{\text{mol}} \times \frac{63.55 \text{ g}}{1 \cancel{\text{mol}}}$$

$$m_{Cu} = 309 \text{ kg}$$

or

$$m_{Cu} = 129 \text{ k}\cancel{\text{g}}\ \cancel{Cu_2S} \times \frac{1 \cancel{\text{mol}}\ \cancel{Cu_2S}}{159.16 \cancel{\text{g}}\ \cancel{Cu_2S}} \times \frac{6 \cancel{\text{mol}}\ \cancel{Cu}}{1 \cancel{\text{mol}}\ \cancel{Cu_2S}} \times \frac{63.55 \text{ g Cu}}{1 \cancel{\text{mol}}\ \cancel{Cu}}$$

$$m_{Cu} = 309 \text{ kg}$$

The theoretical yield of copper would be 309 kg.

(c) $\% \text{ yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$

$$\% \text{ yield} = \frac{285 \cancel{\text{kg}}}{309 \cancel{\text{kg}}} \times 100\% = 92.2\%$$

The percentage yield of copper in this reaction is 92.2%.

11. (a)

$C_{(s)}$	+	$2\ H_{2(g)}$	$\rightarrow$	$CH_{4(g)}$
10.0 kg				m (4.20 kg actual)
12.01 g/mol				16.05 g/mol

$$n_C = 10.0 \text{ k}\cancel{\text{g}} \times \frac{1 \text{ mol}}{12.01 \cancel{\text{g}}}$$

$$n_C = 0.833 \text{ kmol}$$

$$n_{CH_4} = 0.833 \text{ kmol} \times \frac{1}{1}$$

$$n_{CH_4} = 0.833 \text{ kmol}$$

$$m_{CH_4} = 0.833 \text{ k}\cancel{\text{mol}} \times \frac{16.05 \text{ g}}{1 \cancel{\text{mol}}}$$

$$m_{CH_4} = 13.4 \text{ kg}$$

or

$$m_{CH_4} = 10.0 \text{ k}\cancel{\text{g}}\ \cancel{C} \times \frac{1 \cancel{\text{mol}}\ \cancel{C}}{12.01 \cancel{\text{g}}\ \cancel{C}} \times \frac{1 \cancel{\text{mol}}\ \cancel{CH_4}}{1 \cancel{\text{mol}}\ \cancel{C}} \times \frac{16.05 \text{ g } CH_4}{1 \cancel{\text{mol}}\ \cancel{CH_4}}$$

$$m_{CH_4} = 13.4 \text{ kg}$$

$$\% \text{ yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$$

$$\% \text{ yield} = \frac{4.20 \cancel{\text{kg}}}{13.4 \cancel{\text{kg}}} \times 100\% = 31.4\%$$

The percentage yield of methane in this reaction is 31.4%.

(b) If the coal is only 40% carbon, then the percentage yield of methane is increased by a factor of 100/40. The percentage yield of methane in this reaction becomes 31.4% × 100/40 = 78.6%.

Making Connections

12. (a) Water is a preferable (nonpolluting) solvent.
(b) Room temperature reactions don't require energy input.
(c) Drying agents are less acceptable — they add an extra chemical.
(d) Purification is less preferred — it will take energy and maybe more chemicals.
(e) Biomass is preferable because it is a renewable resource.

SECTION 5.6 QUESTIONS

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Understanding Concepts

1. (a) Yield in school experiments can be improved mostly by being careful (e.g., using only clean equipment), following procedure, and using good technique.
   (b) Yields in industrial processes can be improved by adjusting reaction conditions, and sometimes by following a different reaction sequence.
2. (a)

$C_7H_6O_{3(s)}$	+	$C_4H_6O_{3(s)}$	$\rightarrow$	$C_9H_8O_{4(s)}$	+	$C_2H_4O_{2(s)}$
2.00 g		4.00 g				
138.13 g/mol		102.10 g/mol				

$$n_{C_7H_6O_3} = 2.00\ \cancel{g} \times \frac{1\ \text{mol}}{138.13\ \cancel{g}}$$
$$n_{C_7H_6O_3} = 0.0145\ \text{mol}$$
$$n_{C_4H_6O_3} = 4.00\ \cancel{g} \times \frac{1\ \text{mol}}{102.10\ \cancel{g}}$$
$$n_{C_4H_6O_3} = 0.0392\ \text{mol}$$

Since the reactant mole ratio is 1:1, the $C_7H_6O_{3(s)}$ is obviously the limiting reagent for this reaction.

$C_7H_6O_{3(s)}$	+	$C_4H_6O_{3(s)}$	$\rightarrow$	$C_9H_8O_{4(s)}$	+	$C_2H_4O_{2(s)}$
2.00 g				m (2.09 g actual)		
138.13 g/mol				180.17 g/mol		

$$n_{C_7H_6O_3} = 2.00\ \cancel{g} \times \frac{1\ \text{mol}}{138.13\ \cancel{g}}$$
$$n_{C_7H_6O_3} = 0.0145\ \text{mol}$$
$$n_{C_9H_8O_4} = 0.0145\ \text{mol} \times \frac{1}{1}$$
$$n_{C_9H_8O_4} = 0.0145\ \text{mol}$$
$$m_{C_9H_8O_4} = 0.0145\ \cancel{\text{mol}} \times \frac{180.17\ \text{g}}{1\ \cancel{\text{mol}}}$$
$$m_{C_9H_8O_4} = 2.61\ \text{g}$$

or

$$m_{C_9H_8O_4} = 2.00\ \cancel{g}\ \cancel{C_7H_6O_3} \times \frac{1\ \cancel{\text{mol}}\ \cancel{C_7H_6O_3}}{138.13\ \cancel{g}\ \cancel{C_7H_6O_3}} \times \frac{1\ \cancel{\text{mol}}\ \cancel{C_9H_8O_4}}{1\ \cancel{\text{mol}}\ \cancel{C_7H_6O_3}} \times \frac{180.17\ \text{g}\ C_9H_8O_4}{1\ \cancel{\text{mol}}\ \cancel{C_9H_8O_4}}$$
$$n_{C_9H_8O_4} = 2.61\ \text{g}$$

The theoretical yield of Aspirin would be 2.61 g.

   (b) $$\%\ \text{yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$$

$$\%\ \text{yield} = \frac{2.09\ \cancel{g}}{2.61\ \cancel{g}} \times 100\% = 80.1\%$$

The percentage yield of Aspirin in this reaction is 80.1%.

Applying Inquiry Skills

3. (a) **Experimental Design**

A measured sample of sodium silicate is dissolved and reacted with an excess of iron(III) nitrate in solution. The resulting precipitate is filtered, washed, and dried to allow measurement of its mass.

Procedure

A typical student procedure will be very similar to the one created for Investigation 5.5.1. It should be preceded by a calculation to determine what mass of iron(III) nitrate (per gram of sodium silicate) is required to ensure an excess.

(b) **Evaluation**

A percentage yield of 80% is very low for a precipitation reaction. This would probably indicate that the precipitate remained at least partly dissolved in the original solution, or dissolved to some extent in the wash water. Obviously, a different process must be tried to improve the yield.

Making Connections

4. There are many "green" projects for students to research — one example might be the work on fuel cells to allow cars to run on hydrogen, thus reducing pollutant levels significantly.

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5. Student reports will be specific to the educational institution they choose and especially to the person they choose to interview. The report should concentrate on educational requirements, and the nature of the workday.

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5.7 CHEMISTRY IN TECHNOLOGY

PRACTICE

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Understanding Concepts

1. Inspection of the reaction equations shows that all mole ratios in each step are 1:1, so two moles (in total) of hydrochloric acid are produced for each one mole of sodium carbonate produced.
2. The LeBlanc process was expensive because it required using a large amount of fuel for heat.
3. Air pollutants were a matter of personal concern to people affected directly by them in these centuries, but no government had, as yet, considered that controlling pollutants was its responsibility. People in general were not aware of long-term health hazards or, indeed, of specific pollution hazards, other than odours and skin or lung irritation. Also, because industries were smaller and relatively few in number, pollutant effects tended to be local rather than widespread.

PRACTICE

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Understanding Concepts

4. (a) $CaCO_{3(s)} \rightarrow CaO_{(s)} + CO_{2(g)}$

   (b) $CO_{2(g)} + NH_{3(aq)} + H_2O_{(l)} \rightarrow NH_4HCO_{3(aq)}$

   (c) $NH_4HCO_{3(aq)} + NaCl_{(aq)} \rightarrow NH_4Cl_{(aq)} + NaHCO_{3(s)}$

   (d) $2\ NaHCO_{3(s)} \rightarrow Na_2CO_{3(s)} + H_2O_{(g)} + CO_{2(g)}$

   (e) $CaO_{(s)} + H_2O_{(l)} \rightarrow Ca(OH)_{2(s)}$

   (f) $Ca(OH)_{2(s)} + 2\ NH_4Cl_{(aq)} \rightarrow 2\ NH_{3(g)} + CaCl_{2(aq)} + 2\ H_2O_{(l)}$

   (g) $CaCO_{3(s)} + 2\ NaCl_{(aq)} \rightarrow Na_2CO_{3(s)} + CaCl_{2(aq)}$ (from text, p. 247)

5. (i) $CaCO_{3(s)} \rightarrow \cancel{CaO}_{(s)} + \cancel{CO}_{2(g)}$

   (ii) $\cancel{CO}_{2(g)} + \cancel{NH}_{3(aq)} + \cancel{H_2O}_{(l)} \rightarrow NH_{\cancel{4}}\cancel{H}CO_{3\,(aq)}$

   (iii) $NH_{\cancel{4}}\cancel{H}CO_{3(aq)} + NaCl_{(aq)} \rightarrow N\cancel{H_4}Cl_{\,(aq)} + Na\cancel{H}CO_{3(s)}$

   (iv) $2\ Na\cancel{H}CO_{3(s)} \rightarrow Na_2CO_{3(s)} + \cancel{H_2O}_{(g)} + \cancel{CO}_{2(g)}$

   (v) $\cancel{CaO}_{(s)} + \cancel{H_2O}_{(l)} \rightarrow Ca\cancel{(O}H)_{2\,(s)}$

