Stoichiometry

From the Greek *stoikheion* "element" and *metriā* "measure."

Here is a good site introducing stoichiometry, with practice problems, from John L. Park's ChemTeam site.

You might also want to look at the Wikipedia article about stoichiometry here.

Stoichiometry calculations are about calculating the amounts of substances that react and form in a chemical reaction. For example, based on the balanced chemical equation, we can calculate the amount of a product substance that will form if we begin with a specific amount of one or more reactants. Or, you may have a target amount of product to prepare. How much starting compounds are needed to prepare this amount? These are practical calculations that are done frequently by chemists.

The Method

For practically all stoichiometry problems, we want to use the. . . .

Fabulous Four Steps

Step 1: Write the *balanced chemical equation* for the reaction.

Step 2: Calculate the *moles* of "given" substance. If more than one reactant amount is given, calculate the moles of each to determine which is the *limiting reactant*.

Step 3: Calculate the moles of "desired" substance from your answer in Step 2 *using the coefficients from the balanced chemical equation*. If more than one reactant was given originally, you can calculate the moles of product *twice*, based on the moles of each reactant. The reactant that gives the *smaller* moles of product is the limiting reactant. Keep this answer for Step 4.

Step 4: Convert your answer in Step 3 to the *units the problem asks for*. Usually this is grams, but it could be volume (for gases or liquid solutions) or concentration (such as molarity, for solutions).

Again in brief:

1. Balanced reaction
2. Moles of "given" substance(s)
3. Moles of "desired" substance such as a product
4. Convert Step 3 answer to the units asked for

Examples

Example 1: How many grams of ferric oxide, Fe_2O_3, are formed from the reaction of 5.00 g of iron metal with excess oxygen gas?

Step 1: Balanced reaction.
4 Fe (s) + 3 O_2 (g) ——> **2** Fe_2O_3 (s)

Step 2: Moles of "given" substance, the iron metal, since its amount is given.
moles of Fe = grams of Fe / molar mass of Fe = 5.00 g / 55.845 g/mol = 0.08953353 mol (not rounding yet)

Step 3: Moles of "desired" substance, ferric oxide.
Here's where the balanced reaction comes in. The coefficients in the balanced reaction represent the <u>moles</u> of the substances that react and form. As such, balanced reactions are "in" moles by default. That is why we always have to convert amounts to moles when working these kinds of problems.

$$\text{moles of } Fe_2O_3 = \frac{0.08953353 \text{ mol Fe}}{1} \times \frac{\mathbf{2} \text{ mol } Fe_2O_3}{\mathbf{4} \text{ mol Fe}} = 0.044766765 \text{ mol } Fe_2O_3$$

Step 4: Grams of Fe_2O_3
Grams of Fe_2O_3 = moles of Fe_2O_3 X molar mass of Fe_2O_3
= 0.044766765 mol X 159.6882 g/mol = **7.15 g** rounded to 3 significant figures.

And that's it! We can also do steps 2–4 like a conversion problem. Once you are familiar with the steps, you can work these problems more quickly this way.

$$\frac{5.00 \text{ g Fe}}{1} \times \frac{1 \text{ mol Fe}}{55.845 \text{ g Fe}} \times \frac{2 \text{ mol } Fe_2O_3}{4 \text{ mol Fe}} \times \frac{159.6882 \text{ g } Fe_2O_3}{\text{mol } Fe_2O_3} = 7.15 \text{ g of } Fe_2O_3$$

Remember to
1) <u>write the **units** on all numbers</u> and <u>check that the units cancel properly</u> to give the <u>correct unit for the answer</u>, and
2) <u>avoid rounding numbers too much during the calculation</u>, or you will have <u>roundoff error</u> in your answer.

Example 2: If 10.0 g of iron metal is reacted with 15.0 g of Cl_2 gas, how many grams of ferric chloride, $FeCl_3$, will form?

In this problem, the amounts of <u>both</u> reactants are given, so we will have to determine which is the <u>limiting reactant</u> (the one that "limits" the amount of product that is formed). The other reactant is in excess amount. We'll use the Fab Four Steps just as before.

Step 1: Balanced reaction.
$2\ Fe\ (s) + 3\ Cl_2\ (g) \longrightarrow 2\ FeCl_3\ (s)$

Step 2: Moles of given substances.
moles of Fe = 10.0 g / 55.845 g/mol = 0.17906706 mol
moles of Cl_2 = 15.0 g / 70.906 g/mol = 0.211547682 mol

Step 3: Moles of desired substance, $FeCl_3$.
Since we have two given amounts, a straightforward approach to this step is to calculate the moles of $FeCl_3$ <u>twice</u>, first based on the moles of Fe and second based on the moles of Cl_2. <u>Keep the **smaller** answer</u>. <u>The reactant that gives this smaller answer is the limiting reactant</u>. The other reactant is in <u>excess</u> amount.

$$\text{moles of } FeCl_3 \text{ based on Fe} = \frac{0.17906706 \text{ mol Fe}}{1} \times \frac{2 \text{ mol } FeCl_3}{2 \text{ mol Fe}} = 0.17906706 \text{ mol of } FeCl_3$$

$$\text{moles of } FeCl_3 \text{ based on } Cl_2 = \frac{0.211547682 \text{ mol } Cl_2}{1} \times \frac{2 \text{ mol } FeCl_3}{3 \text{ mol } Cl_2} = 0.141031788 \text{ mol of } FeCl_3$$ <— **Keep this answer!**

Since the moles of $FeCl_3$ based on moles of Cl_2 is the smaller answer, <u>Cl_2 is the limiting reactant</u>. Iron metal is therefore in excess amount, so there will be some Fe left over unreacted.

Note that we might have reasonably assumed that iron metal was the limiting reactant since it was present in lesser amount in grams initially (10.0 g of Fe and 15.0 g of Cl_2). But it turned out that Cl_2 was the limiting reactant. The molar masses of the substances and the reaction stoichiometry come into play also, so we can't automatically assume which substance is the limiting reactant until we go through the steps as we did above.

Step 4: Finally! Convert moles of $FeCl_3$ to grams.

Grams of $FeCl_3$ = 0.141031788 mol X 162.204 g/mol = **22.9 g** rounded to 3 significant figures.

Practice makes perfect! Working stoichiometry problems properly will strengthen your skills in working many other types of chemistry problems as well.

Exercises

A good site with a variety of practice problems can be found here. Choose "Reactions" and then "Stoichiometry" from the menu on the left side when you get there. From Dr. Sergei Smirnov's site at New Mexico State University.

1. The combustion of butane occurs according to the following reaction:

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

If we start with 25.0 moles of butane, how many moles of water will form? How many moles of O_2 will be consumed?

2. Calcium carbonate decomposes at high temperature, forming calcium oxide and carbon dioxide according to the following reaction:

$$CaCO_3\ (s) \xrightarrow{\Delta} CaO\ (s)\ +\ CO_2\ (g)$$

If 10.0 kg of $CaCO_3$ is decomposed by this reaction, how many kilograms of CaO will form? How many kilograms of CO_2 will form?

3. Magnesium hydroxide decomposes on heating, forming magnesium oxide and water:

$$Mg(OH)_2\ (s) \xrightarrow{\Delta} MgO\ (s)\ +\ H_2O\ (g)$$

When a sample of $Mg(OH)_2$ was heated in a crucible over a Bunsen burner flame, the weight of the crucible and its contents went from 43.78 g to 42.56 g. How many grams of $Mg(OH)_2$ were initially present?

4. In the reaction of hydrogen sulfide with sodium hydroxide,

$$H_2S\ (g)\ +\ 2\ NaOH\ (aq) \longrightarrow Na_2S\ (aq)\ +\ 2\ H_2O\ (l)$$

how many grams of NaOH are needed to react with 6.75 g of H_2S ?

5. A student prepared bromobenzene in the Organic lab by reacting 10.0 g of benzene, C_6H_6, with bromine in the presence of a ferric bromide catalyst according to the reaction

$$C_6H_6\ (l)\ +\ Br_2\ (l) \xrightarrow[FeBr_3]{} C_6H_5Br\ (l)\ +\ HBr\ (g)$$

If the student obtained 12.9 g of bromobenzene, what was the percent yield?
Percent yield of bromobenzene = actual yield in grams / calculated yield in grams X 100.

6. The complete oxidation of potassium ferrocyanide with potassium permanganate in acidic aqueous solution occurs according to the following reaction:

$$10\ K_4Fe(CN)_6\ (aq) + 218\ H_2SO_4\ (aq) + 122\ KMnO_4\ (aq) \longrightarrow$$
$$122\ MnSO_4\ (aq) + 5\ Fe_2(SO_4)_3\ (aq) + 81\ K_2SO_4\ (aq) + 60\ HNO_3\ (aq) + 60\ CO_2\ (g) + 188\ H_2O\ (l)$$

How many grams of sulfuric acid and potassium permanganate are required to oxidize 25.0 g of potassium ferrocyanide by this reaction? How many grams of carbon dioxide will form?

7. The reaction of magnesium metal with sulfur is carried out according to the following reaction:

$$8\ Mg\ (s) + S_8\ (s) \xrightarrow{\Delta} 8\ MgS\ (s)$$

If 5.00 g of magnesium is heated with 10.0 g of sulfur, how many grams of MgS will form? How many grams of the excess reactant remain?

8. Aluminum oxide is reacted with 6.00 M hydrochloric acid. How many milliliters of 6.00 M HCl are needed to completely react with 15.0 g of Al_2O_3 according to the reaction

$$Al_2O_3\ (s) + 6\ HCl\ (aq) \longrightarrow 2\ AlCl_3\ (aq) + 3\ H_2O\ (l)$$

9. A student reacted a 1.50 g sample containing an unknown amount of zinc metal with excess hydrochloric acid:

$$Zn\ (s) + 2\ HCl\ (aq) \longrightarrow ZnCl_2\ (aq) + H_2\ (g)$$

The volume of hydrogen gas obtained was 244 mL at a temperature of 23.0°C and 1.00 atm. What is the percent by weight of zinc in the sample?

10. Crude iron is obtained in a blast furnace by reaction of iron ore, one component of which is magnetite, Fe_3O_4, with carbon monoxide:

$$Fe_3O_4\ (s) + 4\ CO\ (g) \xrightarrow{\Delta} 3\ Fe\ (l) + 4\ CO_2\ (g)$$

The carbon monoxide, in turn, is prepared in part by the combustion of coke, which is 85 to 90% percent by weight carbon, according to the reaction

$$2\ C\ (s) + O_2\ (g) \longrightarrow 2\ CO\ (g)$$

How many kilograms of Fe_3O_4 are required to prepare 1.00 kg of crude iron? How many kilograms of coke, assumed to be 90% by weight carbon, are needed?

Answers

1. 125 mol of H_2O formed, 162.5 mol of O_2 consumed

2. 5.60 kg of CaO formed, 4.40 kg of CO_2 formed

3. 3.95 g of $Mg(OH)_2$

4. 15.8 g of NaOH

5. 64.2%

6. 145 g of H_2SO_4, 131 g of $KMnO_4$, 17.9 g of CO_2

7. 11.6 g of MgS formed, 3.40 g of sulfur remains as unreacted excess

8. 147 mL of 6.00 M HCl

9. Percent zinc by weight = 43.8%

10. 1.38 kg of Fe_3O_4, 0.319 kg of coke