4.5: Limiting Reagents and Percentage Yield

"If one reactant is entirely used up before any of the other reactants, then that reactant limits the maximum yield of the product."
Problems of this type are done in exactly the same way as the previous examples, except that a decision is made before the ratio comparison is done. The decision that is made is "What reactant is there the least of?"

Example Problem #1

Methane, CH_4, burns in oxygen to give carbon dioxide and water according to the following equation:

$CH_4 + 2\ O_2$ ------> $CO_2 + 2\ H_2O$

In one experiment, a mixture of 0.250 mol of methane was burned in 1.25 mol of oxygen in a sealed steel vessel. Find the limiting reactant, if any, and calculate the theoretical yield, (in moles) of water.

Solution: In any limiting reactant question, the decision can be stated in two ways. Do it once to get an answer, then do it again the second way to get a confirmation.

According to the equation: 1 mol CH_4 = 2 mol O_2
If we use up all the methane then:
1 mol CH_4 = 2 mol O_2
0.25 mol x
x = 0.50 mol of O_2 would be needed.

We have 1.25 mol of O_2 on hand. Therefore we have 0.75 mol of O_2 in excess of what we need.

If the oxygen in is excess, then the methane is the limiting reactant.

Confirmation: If we use up all the oxygen then
1 mol CH_4 = 2 mol O_2
x 1.25 mol
x = 0.625 mol of methane.

We don't have 0.625 moles of methane. We have only 0.25 moles. Therefore the methane will be used up before all the oxygen is. Again the methane is the limiting reactant.

We now use the limiting reactant to make the mole comparison across the bridge to find the amount of water produced.
1 mol CH_4 = 2 H_2O
0.25 mol x

x = 0.50 mol of H_2O would be produced.
Finish off with a statement: When 0.25 mole of methane and 1.25 mole of oxygen are mixed and reacted according to the equation, the methane is the limiting reactant and the maximum yield of water will be 0.50 moles.

Example Problem #2

Chloroform, $CHCl_3$, reacts with chlorine, Cl_2, to form carbon tetrachloride, CCl_4, and hydrogen chloride, HCl. In an experiment 25 grams of chloroform and 25 grams of chlorine were mixed. Which is the limiting reactant? What is the maximum yield of CCl_4 in moles and in grams?
Solution: Start with the equation:

$CHCl_3 + Cl_2$ -------> $CCl_4 + HCl$

Did you check to see if it was balanced?
Calculate the molecular masses of the species needed in the problem.
$CHCl_3$ = 1 C = 1(12.01) = 12.01 Cl_2 = 2 (35.45) = 70.90 g/mol
1 H = 1(1.01) = 1.01 H_2O = 2 H = 2 (1.01) = 2.02
3 Cl = 3(35.45) = 106.35 1 O = 1 (16.00) = 16.00
119.37 g/mol 18.02 g/mol
Then calculate the moles of each of the reactants to be used.
moles of $CHCl_3$ = g / mm = 25.00 g / 119.37 g/mol
= 0.21 moles of $CHCl_3$ are present.
moles of Cl_2 = g / mm = 25.00 g / 70.90 g/mol
= 0.35 moles of chlorine are present.
Decision time: Which of the two reactants do you have the least of?
From the balanced equation you can see that the chloroform and chlorine reactant in a one to one ratio. If we use all the chloroform then we get the following equation.
1 $CHCl_3$ = 1 Cl_2
0.21 mol x
x = 0.21 moles of chlorine are needed.
We need 0.21 moles of chlorine. We have 0.35 moles of chlorine. Therefore chlorine is in excess. The chloroform must be the limiting reactant.
Confirmation: IF we use all the chlorine then:
1 $CHCl_3$ = 1 Cl_2
x 0.35 mol
x = 0.35 moles of chloroform are needed.
If we use all the chlorine then we need 0.35 moles of chloroform. We have only 0.21 moles of chloroform. It is the reactant that we will run out of first. Therefore it is the limiting reactant.
Use the limiting reactant to cross the ratio bridge and find the number of moles of water made.
1 $CHCl_3$ = 2 H_2O
0.21 mol x

x = 0.42 moles of H_2O will be made.
Calculate the grams of water produced.
grams = moles * molecular mass
= 0.42 mol * 18.02 g/mol
= 7.57 grams of water
Finish off with a statement: When 25 grams of each reactant are mixed according to the equation, the chloroform is the limiting reagent and the maximum yield of water will be 0.42 moles or 7.57 grams.

Example Problem #3

Aluminum chloride, $AlCl_3$, can be made by the reaction of aluminum with chlorine according to the following equation:
$2\ Al + 3\ Cl_2$ ------> $2\ AlCl_3$
What is the limiting reactant if 20.0 grams of Al and 30.0 grams of Cl_2 are used, and how much $AlCl_3$ can theoretically form?
Have you checked to make sure the equation is balanced correctly?
Find the molecular masses of all species involved.
Al = 26.98 g/mol Cl_2 = 70.90 g/mol $AlCl_3$ = 133.33 g/mol
Convert the grams into moles.
moles of Al = g/mm = 20.00 g/26.98 g/mol = 0.74 moles of aluminum on hand.
moles of Cl_2 = g/mm = 30.00 g/70.90 g/mol = 0.42 moles of chlorine on hand.
Decision time: Which is the limiting reagent?
IF we use all aluminum then:
$\underline{2\ Al} = \underline{3\ Cl_2}$
0.74 mol x
x = 1.11 moles of chlorine are needed.
We don't have 1.11 moles of chlorine. We have 0.42 moles of chlorine. Therefore we will run out of chlorine first. It is the limiting reactant.
Confirmation:
If we use all the chlorine then:
$\underline{2\ Al} = \underline{3\ Cl_2}$
x 0.42 mol
x = 0.28 moles of aluminum are needed.
We have 0.74 moles of aluminum, therefore it is in excess. If it is in excess then the chlorine is the limiting reactant.
Use the limiting reactant to cross the ratio bridge and find the moles of $AlCl_3$ that will be produced.
$\underline{3\ Cl_2} = \underline{2\ AlCl_3}$
0.42 mol x
x = 0.28 moles of $AlCl_3$ are produced
Grams of aluminum chloride are found with
g = n * mm = 0.28 mol * 133.33 g/mol = 37.33 g
Finishing statement: When 20.0 grams of aluminum and 30.0 grams of chlorine are reacted according to the above equation, the chlorine is the limiting reactant and the maximum yield of aluminum chloride is 0.28 moles or 37.33 grams.

Percentage Yield

In a reaction, ideally all of our limiting reagent is converted into the desired product. This amount of product is call our **theoretical yield**. In practice, however, these theoretical yields are rarely achieved and the amount of product achieved is usually less. This amount of product is called an **actual yield**.

Percentage yield gives us a way to see how efficient a reaction is. The higher the percentage yield the more efficient the reaction because our actual yield is closer to our theoretical yield. We calculate it using the following equation:

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

Example Problem #1
Methanol, CH_3OH, can be made in a synthesis reaction using carbon dioxide and hydrogen:

$$CO_2 + 3\ H_2 \rightarrow CH_3OH + H_2O$$

During an investigation, 20.0 g of hydrogen was reacted with excess carbon dioxide to produce 102.0 g of methanol. What is the percentage yield of this reaction?

Solution:
Step 1: Write the balanced chemical equation, and find the molar masses that we require:

$$CO_2 + 3\ H_2 \rightarrow CH_3OH + H_2O$$

molar $mass_{H2}$ = 2.02 g/mol
molar $mass_{CH3OH}$ = 32.05 g/mol

Step 2: Convert the mass of given substance to moles:

$$moles_{H2} = \frac{mass_{H2}}{molar\ mass_{H2}} = \frac{20.0\ g}{2.02\ g/mol} = 9.90\ mol$$

Step 3: Convert the amount of given substance to amount of required:

$$\frac{3\ mol_{H2}}{9.90\ mol_{H2}} = \frac{1\ mol_{CH3OH}}{n_{CH3OH}}$$

$$n_{CH3OH} = 3.30\ mol$$

Step 4: Convert the moles of required substance to mass of required substance:

$$mass_{CH3OH} = moles_{CH3OH} \times molar\ mass_{CH3O} = 3.30\ mol \times 32.05 \frac{g}{mol} = 105.78\ g$$

Step 5: Calculate the percentage yield:

$$percentage\ yield = \frac{actual\ yield}{theoretical\ yield} \times 100\% = \frac{102.0\ g}{105.78\ g} \times 100\% = 96.4\%$$

SCH4C

Statement: The percentage yield in the synthesis of methanol reaction is 96.4%.

SCH4C

Worksheet 4.5: Limiting Reagents and Percentage Yield

1. Consider the reaction

$$I_2O_{5(g)} + 5\ CO_{(g)} \text{-------}> 5\ CO_{2(g)} + I_{2(g)}$$

a) 80.0 grams of iodine(V) oxide, I_2O_5, reacts with 28.0 grams of carbon monoxide, CO. Determine the mass of iodine I_2, which could be produced?

b) If, in the above situation, only 0.160 moles, of iodine, I_2 was produced.

i) what mass of iodine was produced?

ii) what percentage yield of iodine was produced.

2. Zinc and sulphur react to form zinc sulphide according to the equation.

$$Zn + S \text{---------}> ZnS$$

If 25.0 g of zinc and 30.0 g of sulphur are mixed,

a) Which chemical is the limiting reactant?

b) How many grams of ZnS will be formed?

c) How many grams of the excess reactant will remain after the reaction is over?

3. Which element is in excess when 3.00 grams of Mg is ignited in 2.20 grams of pure oxygen? What mass is in excess? What mass of MgO is formed?

4. How many grams of Al_2S_3 are formed when 5.00 grams of Al is heated with 10.0 grams S?

5. When MoO_3 and Zn are heated together they react

$$3\ Zn_{(s)} + 2\ MoO_{3(s)} \text{----------}> Mo_2O_{3(s)} + 3\ ZnO_{(s)}$$

What mass of ZnO is formed when 20.0 grams of MoO_3 is reacted with 10.0 grams of Zn?

6. Silver nitrate, $AgNO_3$, reacts with ferric chloride, $FeCl_3$, to give silver chloride, AgCl, and ferric nitrate, $Fe(NO_3)_3$. In a particular experiment, it was plannned to mix a solution containing 25.0 g of $AgNO_3$ with another solution containing 45.0 grams of $FeCl_3$.

a) Write the chemical equation for the reaction.

b) Which reactant is the limiting reactant?

c) What is the maximum number of moles of AgCl that could be obtained from this mixture?

d) What is the maximum number of grams of AgCl that could be obtained?

e) How many grams of the reactant in excess will remain after the reaction is over?

7. Solid calcium carbonate, $CaCO_3$, is able to remove sulphur dioxide from waste gases by the reaction:

$$CaCO_3 + SO_2 + \text{other reactants} \text{------}> CaSO_3 + \text{other products}$$

In a particular experiment, 255 g of $CaCO_3$ was exposed to 135 g of SO_2 in the presence of an excess amount of the other chemicals required for the reaction.

a) What is the theoretical yield of $CaSO_3$?

b) If only 198 g of $CaSO_3$ was isolated from the products, what was the precentage yield of $CaSO_3$ in this experiment?

8. A research supervisor told a chemist to make 100 g of chlorobenzene from the reaction of benzene with chlorine and to expect a yield no higher that 65%. What is the minimum quantity of benzene that can give 100 g of chlorobenzene if the yield is 65%? The equation for the reaction is:

$$C_6H_6 + Cl_2 \text{ ----------> } C_6H_5Cl + HCl$$

benzene chlorobenzene

9. Certain salts of benzoic acid have been used as food additives for decades. The potassium salt of benzoic acid, potassium benzoate, can be made by the action of potassium permanganate on toluene.

$$C_7H_8 + 2\ KMnO_4 \text{ -------> } KC_7H_5O_2 + 2\ MnO_2 + KOH + H_2O$$

toluene potassium benzoate

If the yield of potassium benzoate cannot realistically be expected to be more than 68%, what is the minimum number of grams of toluene needed to achieve this yield while producing 10.0 g of $KC_7H_5O_2$?

10. Aluminum dissolves in an aqueous solution of NaOH according to the following reaction:

$$2\ NaOH + 2\ Al + 2\ H_2O \text{ -----> } 2\ NaAlO_2 + 3\ H_2$$

If 84.1 g of NaOH and 51.0 g of Al react:

i) Which is the limiting reagent?

ii) How much of the other reagent remains?

iii) What mass of hydrogen is produced?

Percentage Yield Problems

1. An organic chemist reacted 10 g CH_4 with excess Cl_2 and obtained 10 g of CH_3Cl.

a) What should have been the theoretical yield.

b) What was their percentage yield?

2. An inorganic chemist reacted 100 g of $PbCl_4$ with excess NH_4Cl, obtaining an 87% yield of ammonium chloroplumbate(IV), $(NH_4)_2PbCl_6$. How many grams did they obtain?

3. The synthesis of sulphanilamide, $NH_2C_6H_5SO_2NH_2$, requires six steps beginning with benzene, C_6H_6. If the average yield per step is 80%, how many grams of sulphanilamide will you obtain from 1 kg of benzene?

11. Dimethylhydrazine, $(CH_3)_2NNH_2$, was used as a fuel for the Apollo Lunar Descent Module, with N_2O_4 being used as the oxidant. The products of the reaction are H_2O, N_2, and CO_2.

i) Write a balanced chemical equation for the combustion reaction.

ii) If 150 kg of $(CH_3)_2NNH_2$ react with 460 kg of N_2O_4, what is the theoretical yield of N_2?

iii) If a 30 kg yield of N_2 gas represents a 68% yield, what mass of N_2O_4 would have been used up in the reaction?

12. Magnesium metal reacts quantitatively with oxygen to give magnesium oxide, MgO. If 5.00 g of Mg and 5.00 g of O_2 are allowed to react, what weight of MgO is formed, and what weight of which reactant is left in excess?

13. Adipic acid, $C_6H_{10}O_4$, is a raw material for the making of nylon and it can be prepared in the laboratory by the following reaction between cyclohexene, C_6H_{10}, and sodium dichromate, $Na_2Cr_2O_7$ in sulphuric acid.

$$3\ C_6H_{10}(l) + 4\ Na_2Cr_2O_7(aq) + 16\ H_2SO_4(aq) \longrightarrow 3\ C_6H_{10}O_4(aq) + 4\ Cr_2(SO_4)_3(aq) + 4\ Na_2SO_4(aq) + 16\ H_2O$$

There are side reactions. These plus losses of product during its purification reduce the overall yield. A typical yield of purified adipic acid is 68.6%.

(a) To prepare 12.5 grams of adipic acid in 68.6% yield requires how many grams of cyclohexene?

(b) The only available supply of sodium dichromate is its dihydrate, $Na_2Cr_2O_7.2H_2O$. (Since the reaction occurs in an aqueous medium, the water in the dihydrate causes no problems, but it does contribute to the mass of what is taken of this reactant). How many grams of this dihydrate are also required in the preparation of 12.5 grams of adipic acid in a yield of 68.6%?