VALENCIACOLLEGE

Experiment 4:
Limiting Reactant

Version 5

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In this experiment, you will perform a chemical reaction varying the stoichiometry of the reactants to determine the limiting reactant and excess reactant in each trial. You will also calculate percent yield.

Objectives

- Assess chemical quantities related to compounds (mass, molar mass, moles, molecules/formula units, and percent composition).
- Understand mole relationships among reactants and products in a reaction given a balanced chemical equation.
- Evaluate and apply the concept of solution concentration.
- Calculate the theoretical yield and percent yield in a chemical reaction.

Learning Outcomes

- Understand the factors influencing chemical reactivity and quantitative relationships among species involved in a reaction.
- Employ conceptual learning outcomes and perform essential lab techniques in a laboratory setting.

Definitions

- **Actual yield** – the amount of product obtained in a chemical reaction
- **Coefficients –** numbers in front of the chemical formulas in a chemical equation that specify the relative amounts of each substance, in molecules or moles
- **Excess reactant (**or **excess reagent) –** the reactant that remains at the end of a chemical reaction when the limiting reactant is completed used up
- **Law of conservation of mass –** states that in a chemical reaction, matter is neither created nor destroyed
- **Limiting reactant (**or **limiting reagent) –** the reactant that is completely used up during a chemical reaction, and therefore limits the amount of product that can be formed
- **Molarity, M** – unit of concentration; expressed as moles of solute per liters of solution, mol/L
- **Percent yield –** a percent ratio of the product obtained (actual yield) divided by the theoretical possible amount of product (theoretical yield)
- **Stoichiometry –** the quantitative relationship between substances in a chemical reaction, based upon the law of definite proportions and the law of conservation of mass
- **Theoretical yield –** the amount of product predicted by the reaction stoichiometry

Techniques

- Technique 1: Cleaning Glassware
- Technique 2: Using a Balance
- Technique 5 Video Tech. 5: Using a Volumetric Pipet
- Technique 11: Disposing Chemical Waste
- Technique 17 Video Tech. 17: Filtration by Vacuum

Introduction

Metals are important materials due to their physical properties such as hardness, malleability, ductility, and high melting point.[1] They are used for many structural applications such as ships, buildings, underground tanks, and pipelines. One downside is that metals can be reactive and undergo corrosion especially in the presence of electrolytes (Figure 1); note the white color of the corrosion.[2] In one interesting example, an aluminum tank truck used to transport molasses suddenly showed corrosion, even though molasses does not normally cause this issue.[3] After extensive investigation, it was discovered that one batch of molasses had been made in a copper kettle. And, there were enough copper ions in the molasses from the kettle to cause corrosion of the aluminum tank.

Figure 1. A DC-6/C-118 Liftmaster Made of Aluminum and Fiberglass Shows Corrosion. "Aircraft Restoration" U.S. Air Force Photo by Tech. Sgt. Shawn J. Jones used under the Public Domain.

Today, you will act as a chemical engineer to study the reactivity of aluminum metal in a solution of copper ions. Your supervisor at the Mole of Molasses Bulk Sweets Company would like a general report to share with your supplier of molasses, to try to convince them to discontinue the use of the copper kettles in order to save your tanker trucks.

Chemical reactions are represented by balanced chemical equations. The equation provides a great deal of information about the reaction it represents and the substances involved. The amount of every substance consumed and produced in a chemical reaction is related to the amounts of all the other substances in the equation. According to the law of the conservation of mass, in a chemical reaction, there must be the same number of atoms of each kind on both sides of the equation. Since matter is conserved in a chemical reaction, chemical equations must balance for mass.

For example, consider the reaction between solid phosphorus and gaseous chlorine to produce liquid phosphorus trichloride. As represented by the chemical equation, the total mass of reactants equals the total mass of products.

$$P_4(s) + 6Cl_2(g) \longrightarrow 4PCl_3(l)$$

123.90 g	425.40 g	549.30 g
1 mol	6 mol	4 mol

reactants:	123.90 g	*products:*
	+425.40 g	
	$\boxed{549.30\ g}$	$\boxed{549.30\ g}$

The study of the numerical relationship between chemical quantities in a chemical reaction is called stoichiometry. The stoichiometric coefficients are the numbers in front of the chemical formulas in a balanced chemical equation. The coefficients specify the relative amounts of each substance, in molecules or moles, involved in the reaction. For example, when ethane is burned in the presence of oxygen, carbon dioxide, and water are produced:

$$2\ C_2H_6(l) + 7\ O_2(g) \longrightarrow 4\ CO_2(g) + 6\ H_2O(g)$$

According to the equation, 2 **molecules** of C_2H_6 react with 7 molecules of O_2 to form 4 molecules of CO_2 and 6 molecules H_2O, or 2 **moles** of C_2H_6 react with 7 moles of O_2 to form 4 moles of CO_2 and 6 moles H_2O.

The coefficients allow us to convert between numbers of moles of reactants and reactants, products and products, or reactants and products. The stoichiometric ratio is the ratio of the coefficients of any two species (reactants or products) in a balanced chemical reaction. Conversion factors can be set up to convert from moles of reactants to products or vice-versa using the stoichiometric ratio. For the reactant C_2H_6 and the product CO_2, the conversion factors are:

$$\frac{4\ moles\ CO_2}{2\ moles\ C_2H_6} \quad or \quad \frac{2\ moles\ C_2H_6}{4\ moles\ CO_2}$$

For chemical reactions with multiple reactants, it is likely that one of the reactants will be completely consumed before the others. A reactant that is completely consumed in a chemical reaction is called a limiting reactant or limiting reagent. When this reactant is completely consumed, the reaction stops and no more products are formed since the reaction cannot continue without it.

Returning to the example of ethane, we can ask how many grams of carbon dioxide can be made from 4.00 g of C_2H_6 and 6.00 g of O_2?

$$2C_2H_6(l) + 7O_2(g) \longrightarrow 4CO_2(g) + 6H_2O(g)$$

To solve, first convert mass to moles, since the stoichiometry is based upon moles or molecules:

$$4.00\ g\ C_2H_6 \times \frac{1\ mol\ C_2H_6}{30.070\ g\ C_2H_6} = 0.13\underline{3}0\ mol\ C_2H_6$$

$$6.00\ g\ O_2 = \frac{1\ mol\ O_2}{32.00\ g\ O_2} = 0.18\underline{7}5\ mol\ O_2$$

Note that extra digits are carried through the calculation to avoid rounding errors; the last significant figure is underlined.

Then, use the stoichiometry to determine which reactant will yield less product:

$$0.13\underline{3}0\ mol\ C_2H_6\ \times \frac{4\ mol\ CO_2}{2\ mol\ C_2H_6} = 0.26\underline{6}0\ mol\ CO_2$$

$$0.18\underline{7}5\ mol\ O_2\ \times \frac{4\ mol\ CO_2}{7\ mol\ O_2} = 0.10\underline{7}1\ mol\ CO_2$$

In this case, the oxygen is the reactant that makes the least amount of product; it is the limiting reactant. The maximum amount of the product that can be produced in a chemical reaction is determined by the limiting reactant.

The amount of product that can be produced from the limiting reactant in a chemical reaction is called the theoretical yield of the reaction. For the example of ethane, the theoretical yield is determined by the oxygen since it is the limiting reactant:

$$0.10\underline{7}1\ mol\ CO_2\ \times \frac{44.01\ g\ CO_2}{1\ mol\ CO_2} =\ 4.7\underline{1}3\ g\ CO_2$$

Actual yield is the amount of product obtained experimentally, which may differ from the theoretical for many reasons. The actual yield of the product is expressed as a percentage of the theoretical yield and is called the actual percent yield or just percent yield. For example, if we burn 4.00 g of C_2H_6 and 6.00 g of O_2, and carefully collect the carbon dioxide produced, we may only obtain 4.620 g.

$$\%\ yield = \frac{(Actual\ yield)}{(Theoretical\ yield)}\ x\ 100$$

$$\%\ yield = \frac{4.620\ g}{4.7\underline{1}3\ g}\ x\ 100 = 98.\underline{0}3 =\ 98.0\%\ yield$$

This lower than expected yield occurs in combustion reactions since carbon monoxide (CO) and soot are produced as by-products of the reaction. Percent yield is a unitless quantity. When calculating percent yield, both the theoretical yield and the actual yield must be in the same units. These yield units need not be only in grams; the amount can also be expressed in moles or volume.

In this experiment, one of the reagents will be in solution. So, the moles of reagent will be calculated from volume and a known concentration. For example, if 20.00 mL of 0.25 M copper(II) chloride solution were pipetted into a flask, the number of moles of copper(II) chloride in the flask would be:

$$20.00\ mL\ CuCl_2 \times \frac{1\ L}{1000\ mL} \times \frac{0.25\ mol\ CuCl_2}{1\ L\ solution} = 5.0 \times 10^{-3} mol\ CuCl_2$$

In this experiment, you will add aluminum foil to a known concentration of an aqueous solution of copper(II) chloride. The products of the reaction are solid copper, aqueous aluminum chloride, and water. This is a single displacement reaction, which is also classified as an oxidation-reduction reaction. Aluminum is more active than copper and will displace copper from the copper(II) chloride solution. A red precipitate of metallic copper will form.

$$2\ Al(s) + 3\ CuCl_2(aq) \longrightarrow 3\ Cu(s) + 2\ AlCl_3(aq)$$

Aluminum is a highly reactive silvery-white metal. Usually, the surface of the metal is covered with a very thin layer of oxide (white Al_2O_3) that forms rapidly in air, providing excellent corrosion resistance and protecting the metal from further attack by air. Aluminum does not show its true reactivity until the oxide layer is disturbed.[4] Adding concentrated hydrochloric acid disturbs this oxide layer, and also serves to increase the reaction rate due to the activity of the hydrogen ion.

The stoichiometric ratios of the reactants and the products are known from the balanced chemical equation. The molarity and volume of the copper(II) chloride solution will be given to you; by weighing the aluminum, the limiting reactant in each experimental trial can be determined. Once the limiting reactant is identified, the theoretical yield of the reaction can be calculated. From the experiment results, the actual yield and percent yield of the precipitate formed is determined. You can expect high yield for this reaction (>90%). Make careful observations though since residual aluminum can cause elevated yields, and black copper(II) oxide can be a by-product.

Experimental Procedure

List of Chemicals

- ~0.50 M copper(II) chloride solution
- aluminum foil
- 6 M hydrochloric acid

Hydrochloric acid is corrosive to skin, eyes, and clothing. Copper(II) chloride is toxic via ingestion; be careful to wear gloves, avoid touching face, phone, and other items. Wear appropriate personal protective equipment. Wash hands well before leaving the lab. Use Safety Data Sheet (SDSs) to learn about proper handling of these chemicals. (The SDSs are available in the laboratory or online at www.hazard.com.)

Safety

List of Materials and Glassware

- One 50-mL beaker
- Three 100-mL beakers
- Four 250-mL beakers (or two 250-mL and two 150-mL)
- One watch glass
- One 10-mL graduated cylinder
- One 15-mL volumetric pipet
- Pipet bulb
- Büchner funnel
- Side-arm flask
- Vacuum hose
- Neoprene rubber adapter
- Clamp to hold the side-arm flask
- Filter paper
- Two glass stirring rods
- Oven set at 115 °C (or storage for samples to air dry until next week)

Part A: Identifying the Limiting and Excess Reactant in the Chemical Reaction

In this experiment, you will complete two sets of reactions. Label the two sets of reactions as Trial 1 and Trial 2. You will use 15.00 mL of copper(II) chloride solution, but different masses of aluminum foil for each trial.

Using the periodic table, complete Table 1. You might need these values when doing the calculations.

Record the data measured in this section in Data Table 2 and your observations in Data Table 3.

1. Obtain a 50-mL beaker, a watch glass, and a 10-mL graduated cylinder.
2. Label beaker as 6 M HCl and pour approximately 10 mL of 6 M HCl into it using the 10-mL graduated cylinder. Cover the beaker with the watch glass. Set aside for now.
3. Obtain three clean, dry 100-mL beakers. Label each with one of the following names:
   - $CuCl_2$ S.S.
   - Trial 1
   - Trial 2
4. Pour approximately 50 mL of the copper(II) chloride stock solution (S. S.) into the beaker labeled "$CuCl_2$ S.S." Record the exact concentration of the copper(II) chloride solution written on the label of the bottle in your data table. You will need this concentration to do your calculations.
5. Following the proper procedure, condition a 15-mL pipet with the solution that is in the "$CuCl_2$ S.S." beaker, then pipet 15.00 mL of the solution from the "$CuCl_2$ S.S" beaker into the beaker labeled Trial 1. Using the same pipet, pipet 15.00 mL of the solution that's in your "$CuCl_2$ S.S" beaker into the beaker labeled Trial 2.

Technique 5
Video Tech. 5

6. Cut two pieces of aluminum foil, one approximately 4 cm x 6 cm; the other approximately 6 cm x 6 cm.
7. Obtain two weighing boats. Label them as Trial 1 and Trial 2.
8. Using an analytical balance, place the Trial 1 boat on the balance and tare the boat. Place the smaller aluminum foil on the boat. Make sure the mass of the aluminum foil is between 0.09 and 0.11g (if it measures more break a piece off, if it measures less add another piece of aluminum foil - it does not have to be a whole piece, it can be several pieces). Write the actual mass of the aluminum foil displayed on the balance in your data table.

Technique 2

9. Next, using the same analytical balance, place the Trial 2 boat on it and tare the boat. Place the larger aluminum foil on the boat. Make sure the mass of the aluminum foil is between 0.135 and 0.145g. Write the actual mass of the aluminum foil displayed on the balance in your data table.
10. You must perform the following part of the experiment in a fume hood or under a snorkel fume extractor:
    a. Cut the smaller aluminum foil into small pieces, collecting the cuttings in the Trial 1 boat. (Smaller pieces increase the reaction rate).
    b. Cut the larger aluminum foil into small pieces, collecting the cuttings in the Trial 2 boat.
    c. Record observations and color of the solution in each beaker and the aluminum foil in your data table (Table 3).
    d. Note the time, then place the foil in the Trial 1 boat into the Trial 1 beaker containing the copper(II) chloride solution. Then transfer the foil that's in the Trial 2 boat into the Trial 2 beaker containing the copper(II) chloride solution.

e. For the next ten minutes, stir the solution in each beaker every minute, using two glass stirring rods. Break up the chunks of copper forming with the stirring rod to allow all the aluminum to react.
f. Once the ten minutes have passed, measure 2.0 mL of 6 M HCl in the 10-mL graduated cylinder. Add the acid to the beaker labeled Trial 1 and stir the solution. Measure another 2.0 mL of the 6M HCl acid and add it to the beaker labeled Trial 2.
g. Continue stirring both reaction mixtures regularly for 10 more minutes. Then add 2.0 mL more of the HCl to each beaker.
h. Stir the reaction for 10 more minutes.
i. Inspect it carefully to see if the reaction is complete. The reaction is complete when no more bubbles or effervescence are observed, and all the aluminum disappears. If it is still reacting, add an additional 2.0 mL of 6 M HCl. Stir one more time and let it sit for a few minutes (2-4 minutes).

While waiting, use this time to have one group member stir while the other sets up the filtrations for Part B.

11. Allow the reaction mixture to settle. Record your observations for the content of each beaker in your data table.

Part B: Filtration and Measuring the Product

You will perform vacuum filtration to separate the copper product. Record the data collected from this section in Data Table 4.

Technique 17
Video Tech. 17

1. Obtain and label two 150-mL or 250-mL beakers (Trial 1 and Trial 2 and your initials). Measure the mass of each labeled beaker and record the masses in your data table.
2. Obtain two filter papers. Label outer edge of the filter papers using a pencil (Trial 1 and Trial 2 and your initials). Measure the mass of each labeled filter paper, record the masses in your data table.
3. Obtain a Büchner funnel, side-arm flask, vacuum hose, and a clamp. Set up the vacuum-filtration system following Technique 17.
4. Filter the Trial 1 solution through the vacuum-filtration system:
    a. Pour the supernatant solution from the beaker onto the filter paper using a glass stirring rod to direct the flow.
    b. Add 15 – 20 mL of distilled water into the beaker containing the solid copper and stir using the glass rod (to remove any excess acid trapped in the precipitate.) Allow the solid to settle and transfer the supernatant solution from the beaker onto the filter paper.
    c. Transfer the entire solid onto the filter paper.
    d. Thoroughly rinse the sides of the filter paper and the residue (red-colored solid copper) in the filter paper with distilled water.
    e. Leave the residue on the filter paper until all the water is completely drained.

5. Transfer each filter paper containing the copper from Büchner funnel to the corresponding beakers labeled Trial 1 and Trial 2.
6. Heat beakers with the filter paper and solid copper for 15–20 minutes in an oven at 115 °C to dry them.
7. Using the tongs and hot gloves, remove the heated beakers containing the filter paper with the solid copper from the oven. Place each on a hot pad to cool.
8. After cooling, weigh each beaker with the filter paper and the solid copper. Record the masses in your data table.
9. Place each beaker with the filter paper and the solid copper back in the oven and continue heating for 5 more minutes. Allow it to cool, and re-mass. Continue heating, cooling, and weighing (two more times if required), until you get a constant mass (± 0.01 g between two consecutive masses) for the beaker with the filter paper and the solid.

The last mass obtained after the heating and cooling is used for calculating the final mass of the solid product formed in the reaction. This mass is your experimental or actual yield. Note: It is incorrect to take the average of all the masses measured while drying. The average will not give you the accurate mass of the final solid product. Use the last mass only.

Part C: Calculations

Complete the calculations required in Tables 5 and 6. Don't forget to add a title to these two tables and to show your calculations.

Clean up/Disposal

Technique 11

- Pour all liquid waste into the liquid waste container. Rinse the beaker and any glassware with small portions of water and discard the rinses in the liquid waste container.
- Solid waste must be discarded in the solid waste container.
- Clean the glassware with soap and tap water, and discard in the sink. Rinse it twice with distilled water, dry the outside of the glassware, and replace in its original location.
- Place the volumetric pipets tip up in the pipet canister.

References

1. Chemistry Libretexts. *Metals, Nonmetals, and Metalloids.* https://chem.libretexts.org/Textbook_Maps/General_Chemistry_Textbook_Maps/Map%3A_Chemistry%3A_The_Central_Science_(Brown_et_al.)/07._Periodic_Properties_of_the_Elements/7.6%3A_Metals%2C_Nonmetals%2C_and_Metalloids, accessed June 19, 2017.

2. Chemistry Libretexts. *Sacrificial Anode.* https://chem.libretexts.org/Core/Analytical_Chemistry/Electrochemistry/Case_Studies/Corrosion/Sacrificial_Anode, accessed June 18, 2017.

3. *Understanding the Corrosion Behavior of Aluminum.* Corrosion of Aluminum and Aluminum Alloys; Davis, J. R., Ed.; ASM International: Materials Park, OH, 1999; p. 39.

4. Sobel, Sabrina G.; Cohen, Skyler. Spectator IONS Are Important! A Kinetic Study of the Copper-Aluminum Displacement Reaction. *J. Chem. Ed.* **2010**, *87 (6), 616-618.*

Pre-lab

The pre-lab assignment must be completed before you come to the lab.

1. Given the chemical reaction: *$Fe(s) + CuSO_4(aq) \rightarrow FeSO_4(aq) + Cu(s)$*, answer the following questions.

   a. Is the chemical equation above balanced?
   b. Using the coefficients from the balanced chemical equation for the above reaction; write the mole-to-mole ratio between each of the reactants and solid product (copper.)

2. Write the balanced chemical equation for the reaction between solid aluminum and aqueous solution of copper(II) chloride.

   a. Using the coefficients from the balanced chemical equation for the above reaction; write the mole-to-mole ratio between each of the reactants and solid product (copper.)
   b. Determine the molar mass of aluminum metal and copper metal.
   c. Determine how many moles of copper(II) chloride are in 15.00 mL of a 0.500M solution.
   d. When 0.200 grams of Al reacts with 15.00 mL of a 0.500 M copper(II) chloride solution, how many moles of solid Cu would be produced? How many grams of solid Cu would be produced? Show all calculations including the mole-to-mole ratios used in the calculation.
3. If the solid copper product is recorded with the following information in the excerpt of Table 3 below, what should be recorded for the mass of copper product formed in the experiment (actual yield) in the last cell?

Table 3. Mass of Product

Trial 1	
Mass of empty beaker	29.570 g
Mass of filter paper	0.331 g
Mass of beaker + filter paper + copper product, after:	
First heating	30.254 g
Second heating	30.253 g
Third heating	30.253 g
Final mass of beaker + filter paper + copper product, after heating	30.253 g
Mass of copper product formed in the experiment (actual yield)	?

Post-lab

Hand in Tables 1-6 and show your calculations neatly for ***each*** trial.

Experiment 4: Limiting Reactant
Experimental Data and Calculations

Name: ______________________________ **Date:** ________________

Lab Partner: ______________________________ **Section:** __________

Experimental Data and Calculations

Remember to include units of measure with each entry, and to read and record each measurement to the full precision allowed by the instrument used. All tables should have a title - add where needed.

Table 1. Molar Mass of Reactants and Solid Product

1. Molar mass of copper(II) chloride	
2. Molar mass of Al metal	
3. Molar mass of Cu metal	

Table 2. Amount of Reactants Used in Each Trial

1. Trial #	Trial 1	Trial 2
2. Molarity of copper(II) chloride solution		
3. Volume of copper(II) chloride solution		
4. Moles of copper(II) chloride		
5. Mass of Al foil		
6. Moles of Al		

(Note: the clear cells should contain your data; the shaded cells will contain calculated values.)

Show your work for Trial 1:

Table 3. Observations of Reactants and Products

Observations	Trial 1	Trial 2
Reactants before mixing		
Mixture after reaction complete		

Table 4. Amount of Copper Produced in Each Trial

1. Trial #	Trial 1	Trial 2
2. Mass of empty beaker		
3. Mass of filter paper		
4. Mass of beaker + filter paper + solid product, after:		
a. First heating		
b. Second heating		
c. Third heating		
d. Final mass of beaker + filter paper + product, after heating		
5. Mass of solid copper formed in the experiment (actual yield)		

Show your work for Trial 1:

Table 5. ____

Balanced Equation: $2\ Al(s) + 3\ CuCl_2(aq) \longrightarrow 3\ Cu(s) + 2\ AlCl_3(aq)$		
1. Trial #	Trial 1	Trial 2
2. Moles of Cu(s) theoretically formed if $CuCl_2$ completely reacts		
3. Moles of Cu(s) theoretically formed if Al completely reacts		
4. Chemical formula of the limiting reactant		
5. Chemical formula of the excess reactant		
6. Theoretical yield in moles of Cu(s)		
7. Theoretical yield in grams of Cu(s)		
8. Theoretical mass of the unreacted excess reactant		

Show your work for each type of calculation for each trial:

Table 6. ______________________________________

1. Trial #	Trial 1	Trial 2
2. Actual yield (mass of solid copper formed in the experiment)		
3. Theoretical yield		
4. Percent yield		

Show your work for each type of calculation for each trial: