STUDENT ACTIVITY GUIDE

How does the International Space Station produce enough oxygen to keep the astronauts alive?

The challenge

Astronauts living aboard the International Space Station conduct experiments, carry out maintenance projects, eat, sleep, and exercise, all while traveling through space at 5 miles per second and orbiting 250 miles above Earth. Rotating crew members and visitors from more than 20 countries have been living and working at the station since the year 2000.

Here on Earth, we typically take for granted the ready supply of air to breathe, but what happens if you're living in space? How does the space station provide oxygen for people to survive outside of Earth's atmosphere for months at a time? And how can the astronauts be sure that every person on board will have enough oxygen each day? In this activity, you'll investigate how chemical reactions can be designed to produce specific amounts of products and learn how this approach is used to keep the astronauts alive on the International Space Station.

By the end of this activity, I will be able to…

- use stoichiometry to predict the theoretical yield of a chemical reaction or the amount of reactants required to make a desired amount of product
- collect and analyze data from a chemical reaction to determine percent yield
- assess the effectiveness of an experimental procedure based on percent yield

Setting the stage

Before we get to the space station, let's review some key concepts related to quantifying the relationships between reactants and products in chemical reactions.

Start by writing a balanced chemical equation, including the states of matter, for the reaction below.

> *Solid magnesium metal reacts with aqueous aluminum chloride to produce solid aluminum and aqueous magnesium chloride.*

_________________ + _________________ → _________________ + _________________

Since atoms, ions, and molecules are so incredibly tiny, we talk about them in terms of very large groups of particles. A group of **6.022 x 10^{23} particles (Avodagro's number)** is called one ____________________________. The coefficients of a balanced chemical equation can be interpreted as the ratios in which reactants are consumed and products are created during the reaction ***in terms of moles***.

For example, in the reaction above, _________________ moles of magnesium react with _________________ moles of aluminum chloride to give us _________________ moles of aluminum and _________________ moles of magnesium chloride.

Based on these mole ratios, we can determine how many moles of magnesium would be needed to react with 1.50 moles of aluminum chloride. Fill in the mole ratio below and solve for moles of magnesium.

$$(1.50\ moles\ aluminum\ chloride) \times \left(\frac{\underline{\qquad\qquad}\ moles\ magnesium}{\underline{\qquad\qquad}\ moles\ aluminum\ chloride}\right) =$$

$$\underline{\qquad\qquad\qquad}\ moles\ magnesium$$

Moles provide a convenient way to quantify the outcome of a chemical reaction, but the way we ***measure*** the amount of matter in a sample is by using a balance to find its **mass** in grams. Therefore, we use **molar mass** to relate these two quantities.

Molar mass is the mass in grams of one ____________________________ of a substance.

The molar mass of any element can be found in the ______________________________. The molar mass of a compound is determined by adding the molar masses of all its constituent atoms. For example, find the molar mass of magnesium chloride ($MgCl_2$):

Molar mass of magnesium: ______________________________

Molar mass of chlorine $(\times\ 2)$: ______________________________

Molar mass of magnesium chloride: ______________________________

Show how molar mass can be used to **convert between moles and grams** of any substance by filling in the **conversion factors** below and solving for the desired values.

Find the number of moles of $MgCl_2$ in 2.00 g of $MgCl_2$:

$$\left(2.00\ g\ MgCl_2\right) \times \left(\frac{\qquad\qquad}{\qquad\qquad}\right) = \underline{\hspace{4cm}}\ moles\ MgCl_2$$

Find how many grams of $MgCl_2$ are needed to have 0.20 moles of $MgCl_2$:

$$\left(0.20\ moles\ MgCl_2\right) \times \left(\frac{\qquad\qquad}{\qquad\qquad}\right) = \underline{\hspace{4cm}}\ grams\ MgCl_2$$

The **theoretical yield** of a reaction is the calculated amount of product that could be created if all of an available reactant were consumed.

For example, we could predict the maximum number of grams of aluminum that could be produced if 5.00 g of magnesium reacted with excess aluminum chloride according to the balanced chemical equation you wrote earlier. Fill in the appropriate values below to solve for the theoretical yield of aluminum.

$$(5.00\ g\ Mg) \times \left(\frac{1\ mole\ Mg}{\qquad\ g\ Mg}\right) \times \left(\frac{\qquad\ moles\ Al}{\qquad\ moles\ Mg}\right) \times \left(\frac{\qquad\ g\ Al}{1\ mole\ Al}\right) =$$

$$\underline{\hspace{4cm}}\ g\ Al$$

The amount of product collected at the end of a chemical reaction, when it is carried out in the laboratory, is called the **actual yield**. One way to quantify the success of a reaction is to compare the theoretical and actual yields by calculating **percent yield**:

$$percent\ yield\ =\ \left(\frac{actual\ yield}{theoretical\ yield}\right) \times\ 100\%$$

Let's get started!

Materials

- water
- calcium chloride
- sodium carbonate
- 1 balance (or kitchen scale)
- 1 spatula (or small spoon)
- 1 stirring rod (or small spoon)
- 1 small/medium-sized funnel
- aluminum foil
- drying oven (optional)
- 2 beakers-150 mL (or other similar sized clear containers)
- 1 graduated cylinder-25 mL (or kitchen measurement tool for volume)
- 1 weigh boat (or small container for measuring mass on the balance)
- 1 piece of filter paper (or coffee filter)
- tape/marker for labeling
- scientific calculator

Investigation

In Part 1 of this activity, you'll use stoichiometry to make predictions about a reaction between calcium chloride and sodium carbonate. In Part 2, you'll carry out this chemical reaction and compare the experimental outcome to your predictions. Finally, you'll explore how an understanding of stoichiometry and theoretical yield can ensure that astronauts on the space station have adequate oxygen to survive.

Part 1: Using stoichiometry to make predictions

1. Write a balanced chemical equation for the reaction between aqueous calcium chloride and aqueous sodium carbonate to produce solid calcium carbonate and aqueous sodium chloride.

2. Suppose you want to produce 2.00 g of calcium carbonate from this chemical reaction. Answer the following questions and fill in **Table A** below.

   a) How many moles of calcium carbonate are in 2.00 g of calcium carbonate?

   b) What is the minimum number of moles of calcium chloride needed to react in order to make this desired amount of calcium carbonate product? How many grams of calcium chloride is this?

   c) What is the minimum number of moles of sodium carbonate needed to react to make this desired amount of calcium carbonate product? How many grams of sodium carbonate is this?

d) What is the maximum amount of sodium chloride, in moles and grams, that could be produced from this reaction, along with 2.00 g of calcium carbonate?

Table A: Predicted mass and moles of reactants and products

	Calcium chloride	**Sodium carbonate**	**Calcium carbonate**	**Sodium chloride**
Mole ratio (from balanced chemical equation)				
Moles				
Mass (grams)			2.00	

Part 2: Collecting and analyzing reaction data

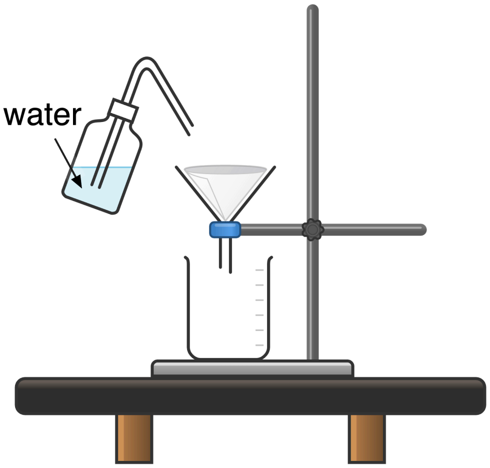
In this experiment, you will combine aqueous solutions of calcium chloride and sodium carbonate, observe the chemical reaction, and collect the solid calcium carbonate product. By comparing the actual mass of product recovered in your experiment to the predicted mass of the product from Part 1, you will analyze the effectiveness of your process.

Experimental procedure:

1. Label two beakers as #1 and #2.
2. Find the mass of solid calcium chloride that you entered in the shaded row of **Table A** above. Using a balance and a weigh boat, measure this number of grams and transfer it

to beaker #1. Record the measured mass value to the appropriate level of precision, based on the balance, in **Table B** below.

3. Using a graduated cylinder, measure 25 mL of water. Add it to beaker #1, and stir until all of the calcium chloride is completely dissolved.
4. Find the mass of solid sodium carbonate that you entered in the shaded row of **Table A** above. Using a balance and a weigh boat, measure this number of grams and transfer it to beaker #2. Record the measured mass to the appropriate level of precision, based on the balance, in **Table B** below.
5. Using a graduated cylinder, measure 25 mL of water. Add it to beaker #2, and stir until all of the sodium carbonate is completely dissolved.
6. Pour the contents of beaker #1 into beaker #2. Gently swirl the beaker and observe the reaction.
7. Measure the mass of a piece of clean, dry filter paper, and record the value in **Table B**.
8. Fold the filter paper into quarters to make a cone, then place it into the funnel. Hold or suspend the funnel with a ring stand above empty beaker #1, as shown in the diagram below.
    - ***Tip:*** Use water to wet the filter paper, once it is in the funnel, so that it sticks to the sides of the funnel.



9. Slowly and carefully pour the reaction mixture from beaker #2 through the funnel.
    - ***Tip:*** If you pour too quickly, the reaction mixture may rise above the edge of the filter paper and pass through the funnel without going through the filter. Pour slowly to ensure that all of the solid gets trapped in the filter.
10. Once all of the liquid has drained through the filter paper, obtain about 10 mL of water in a graduated cylinder, and gradually pour it into the funnel to rinse the solid product. Repeat this process two more times.
11. After all of the rinse water drains through, carefully remove the wet filter paper, and place it on a piece of aluminum foil. Gently unfold and spread out the filter paper, being careful not to tear it.
12. Label the aluminum foil with the names of your lab team members, then place the foil with the filter paper and solid in the appropriate drying location designated by your teacher.
13. When the solid calcium carbonate product is dry, use a balance to measure the mass of the filter paper and product, and record the value in **Table B**.
14. Subtract the mass of the filter paper from the mass of the filter paper + calcium carbonate to determine the mass of the calcium carbonate product you were able to recover from your reaction.

Table B: Experimental mass of reactants and products

Substance	**Mass (grams)**
calcium chloride added	
sodium carbonate added	
clean dry filter paper	
filter paper + calcium carbonate after drying	
calcium carbonate recovered	

Follow-up questions (Part 2)

1. The predicted mass of calcium carbonate that you recorded in **Table A** is the **theoretical yield** of the reaction. The experimental mass of calcium carbonate in **Table B** (the amount you physically collected from the experiment) is the **actual yield** of the reaction. Use these two values to find the **percent yield** of your reaction.

2. If a percent yield value is *greater* than 100%, what does it indicate about the product?

3. If a percent yield value is *less* than 100%, what does it indicate about the product?

4. Consider your experimental procedure.
   a) What happened to the sodium chloride produced in this reaction?

b) Why was it necessary to rinse the solid product with water when it was in the filter?

c) Why was it necessary to dry the product completely?

d) What could lead to “extra” mass in the product?

e) What could lead to “lost” product mass?

5. Why is it sometimes advantageous to intentionally add excess of one reactant in a chemical reaction?

6. If you could repeat this experiment, what would you do differently in order to improve your percent yield?

Part 3: Applying stoichiometry to a practical problem

Each crew member aboard the International Space Station (ISS) requires a little less than a kilogram of oxygen per day, on average. While some oxygen is shipped from Earth aboard supply shuttles, most of it must be produced on board the space station via electrolysis of water, a process in which an electrical current is used to decompose water into its elements. There is also a backup solid-fuel oxygen generator (SFOG) that uses replaceable cartridges, or "candles," containing solid lithium perchlorate. When these cartridges are ignited, they produce oxygen by decomposing lithium perchlorate into lithium chloride and oxygen gas at high temperatures (450-500 ^{o}C).

Understanding the oxygen requirements of the crew members on board and the theoretical yield of each oxygen generation process allows astronauts to effectively utilize the ISS life support systems.

1. Write a balanced chemical equation for the separation of liquid water into hydrogen and oxygen gases during the process of electrolysis. (*Hint: remember your diatomic elements!*)

2. If 2.50 kg of water undergoes electrolysis on the ISS each day, what mass of oxygen gas theoretically can be produced per day by this method? If each person requires 0.90 kg of oxygen per day, how many crew members could this sustain?

3. Write a balanced chemical equation to represent lithium perchlorate breaking down into lithium chloride and oxygen gas.

4. Suppose a crew of three astronauts had to rely solely on the backup SFOG system for two days.

   a) How many kilograms of oxygen would they need to generate? How many grams is this? (Assume each crew member needs 0.90 kg of oxygen per day.)

   b) How many kilograms of lithium perchlorate would they need to decompose?

   c) If each oxygen "candle" contains 2 kg of lithium perchlorate, what is the minimum number of candles they would need to have on board to survive?

Keep creating!

It turns out that producing sufficient oxygen is only one aspect of keeping astronauts alive in space. To keep the air breathable over time, systems must be in place to remove the carbon dioxide that astronauts exhale and to filter out particulate matter and microorganisms. They also need water for drinking, preparing food, and cleaning. In order for long-term deep space missions to be possible, engineers will need to develop even more efficient self-contained life support systems like NASA's Environmental Control and Life Support System (ECLSS) currently in use on the ISS. A mission to Mars, for example, would require about 18 months of round-trip travel and another 2-6 months of research on the planet, all without the possibility of resupplying resources.

Do some research to learn more about the ECLSS and how its different systems work together to recycle and reuse precious resources (including 90 percent of all sweat and urine!) to keep the astronauts alive.

Imagine that you are a crew member on the first mission to Mars. Write a journal entry explaining to friends and family back home on Earth how it feels to be in this new environment and to rely on the different parts of the ECLSS for your survival.

Include an explanation of at least one of the following:

- How the Water Recovery System recycles wastewater and why this is essential for the functioning of the Oxygen Generation System
- The role of the Air Revitalization System in removing contaminants, especially carbon dioxide, from the atmosphere
- How the Sabatier Reactor makes water from two different waste products

More creative activities!

Below are some ideas for how you can use your creativity and your understanding of stoichiometry to generate new ideas and solutions.

- The active ingredients in most pharmaceuticals, from over-the-counter pain medications like ibuprofen to drugs that treat diabetes, are organic molecules that must be produced through a series of chemical reactions. Each reaction requires a certain ratio of reactants and will result in a certain percent yield after the product is isolated. In order to make this process most efficient and cost effective, chemists use stoichiometry to determine the precise amounts of reactants needed to produce a desired amount of product in the highest yield possible for every reaction step.

  A group of pharmaceutical executives is looking for ways to reduce expenses, and they want to understand how chemistry can help. Create a slide presentation for the executives in which you explain:

  - How stoichiometry can be used to determine the amounts of reactants needed to produce a desired amount of product in a chemical reaction
  - Some factors that could affect the cost and efficiency of a chemical reaction step in the production of a pharmaceutical
  - How stoichiometry can be used to maximize yield and minimize waste and cost in pharmaceutical production

- Mole Day, celebrated each year on October 23rd (10/23) from 6:02 am to 6:02 pm, commemorates the power of Avogadro's number (6.02×10^{23}) in our lives. Design a creative poster for your chemistry classroom that celebrates the mole and demonstrates how it can be applied in at least one interesting situation.