TEACHER GUIDE

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

Overview

In this hands-on activity, students first will use stoichiometry to make predictions about a reaction between calcium chloride and sodium carbonate. Next, they will carry out the reaction, compare the experimental outcome to their predictions, and assess the effectiveness of their procedures. Lastly, they will explore how an understanding of stoichiometry and theoretical yield can ensure that astronauts aboard the International Space Station have adequate oxygen to survive.

Standards

NGSS Performance Expectations

- **HS-PS1-7.** Use mathematical representations to support the claim that atoms, and therefore mass, are conserved during a chemical reaction.

NGSS SEPs/DCIs/CCCs

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
• Planning and carrying out investigations • Analyzing and interpreting data • Developing and using models • Constructing explanations and designing solutions	**PS1.B: Chemical Reactions** • The fact that atoms are conserved, together with knowledge of the chemical properties of the elements involved, can be used to describe and predict chemical reactions.	• Patterns • Cause and effect • Energy and matter • Stability and change

Prerequisites

Before doing this activity, students should be familiar with the following concepts:

- Writing chemical formulas for ionic compounds
- Writing balanced chemical equations
- Determining the molar mass of a compound
- Converting between moles and mass
- Mass to mass stoichiometry calculations
- Calculating percent yield of a chemical reaction

See this activity's article on Khan Academy for links to related videos, articles, and practice exercises.

Essential questions

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

Materials

- For each student:
  - student activity guide (provide paper copies or assign digitally)
  - periodic table
  - scientific calculator
- For each group:
  - water
  - 3 g calcium chloride
  - 3 g sodium carbonate
  - 1 balance (or kitchen scale)
  - 1 weigh boat
  - 1 spatula (or small spoon)
  - 1 stirring rod (or small spoon)
  - tape/marker for labeling
  - 2 beakers-150 mL (or other similar sized clear containers)
  - 1 graduated cylinder-25 mL (or kitchen measurement tool for volume)
  - 1 small/medium-sized funnel
  - 1 piece of filter paper (or coffee filter)
  - aluminum foil
  - drying oven (optional)

Implementation suggestions

- Approximate time to allot for each section:
    - *Setting the stage* (15 minutes)
    - *Part 1: Using stoichiometry to make predictions* (20 minutes)
    - *Part 2: Collecting and analyzing reaction data*
        - Data collection (30 minutes + drying time)
        - Follow-up questions (25 minutes)
    - *Part 3: Applying stoichiometry to a practical problem* (20 min)
    - *Let's get creative!* (Consider allocating an additional class period for this activity or assigning it as homework.)
- The time allotments above are suggestions and may vary depending on the needs of your class.
- Notes on set-up and safety:
    - Divide students into pairs or small groups for laboratory work.
    - It is best to use the anhydrous salts of calcium chloride and sodium carbonate. Although the hydrates will react in the same manner as the anhydrous salts, you will need to provide students with the adjusted chemical formulas. It will be necessary to take into account the added mass of the water molecules in the hydrate crystals when students calculate molar mass to make their predictions.
    - Remind/show students how to properly operate and tare a balance.
    - Demonstrate how to fold a piece of filter paper to create a cone for filtering, and encourage students to pour slowly and carefully during the filtration process.
    - If a drying oven is available, students may be able to dry and collect mass data for their product samples in the same class period. If not, the samples may be left overnight to dry, and time should be allotted in the following class period for students to make final measurements.
    - **Waste disposal**: All materials used in the activity can be safely washed down the drain, but it is generally good laboratory practice to collect waste in a central location. This way, you can ensure proper disposal at the end of the class period.
    - **Safety**: If safety goggles are available, these should be worn. Remind students to treat all materials with caution, to wipe up any spills immediately, and to alert the teacher if there are any questions or concerns.

Possible misconceptions

- **Incorrect:** The coefficients of a balanced chemical equation relate the reactants and products in terms of grams.
    - **Correct:** The coefficients of a balanced chemical equation indicate the ratios between reaction components in terms of individual particles of each substance (e.g., atoms, molecules, or formula units). Since a mole represents a specific number of particles, the coefficients also relate reactants and products in terms of moles. The ratio does not hold true for mass, however, because particles of different substances have different masses.

- **Incorrect:** Stoichiometry determines the amount of product that will be produced in an experiment.
    - **Correct:** Stoichiometry allows us to predict the maximum amount of product that can be produced by a chemical reaction under ideal conditions when all of the limiting reactant is consumed and no byproducts are formed. This does not take into account experimental error or the likelihood that mass will be "lost" in the process of collecting and isolating products. As a result, the actual yield of a reaction is typically less than the theoretical yield predicted by stoichiometric calculations.

Support for multilingual learners

- Solicit students' prior knowledge and experiences related to this topic.
- Use visuals (photos, diagrams, videos) to build background knowledge, illustrate the goals of the activity, and show how students will set up the investigation and collect data.
- Use targeted language support. Introduce cognates and diagrams to scaffold understanding.
- Use home language resources such as digital translation tools to translate written instructions into students' home languages.
- Be strategic in grouping students, so that students who are new English language learners are teamed with students who have greater fluency in English.
- Provide alternative ways for students to demonstrate their learning. For example, students could share their responses to the creativity follow-ups in a variety of ways.
- Provide a graphic organizer for the creativity follow-ups to support students in organizing their ideas.

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Support for students with disabilities

- Provide multiple modalities for accessing the text and information in the activity. These could include diagrams, text readers, read-aloud activities or chunking text into smaller pieces.
- Provide additional visual scaffolds, including diagrams and videos.
- Break the investigation into discrete chunks so that students can tackle smaller subsets of the investigation procedure.
- Provide a graphic organizer for the creativity follow-ups to support students in organizing their ideas.

Answer key

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.*

______*3 Mg (s)*______ + ______*2 $AlCl_3$ (aq)*______ → ______*2 Al (s)*______ + ______*3 $MgCl_2$ (aq)*______

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 _________*mole*_________________. 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, _______*three*_______ moles of magnesium react with _____*two*___________ moles of aluminum chloride to give us _______*two*________ moles of aluminum and _____*three*________ 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.

$$(1.50 \; moles\ aluminum\ chloride) \times \left(\frac{3 \;\; moles\ magnesium}{2 \;\; moles\ aluminum\ chloride}\right) = \underline{\;2.25\;} \; moles\ magnesium$$

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 ________*mole*__________________ of a substance.

The molar mass of any element can be found in the _____*periodic table*_____________. 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: _______*24.31 g/mol*_____________

Molar mass of chlorine $(\times\ 2)$: ____*(35.45 g/mol)(2) = 70.90 g/mol*__

Molar mass of magnesium chloride: ____*95.21 g/mol*______________

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 $MgCl_2$:

$$\left(2.00\ g\ MgCl_2\right) \times \left(\frac{1\ mole\ MgCl_2}{95.21\ g\ MgCl_2}\right) = \underline{\quad 0.0210 \quad}\ moles\ MgCl_2$$

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

$$\left(0.20\ moles\ MgCl_2\right) \times \left(\frac{95.21\ g\ MgCl_2}{1\ mole\ MgCl_2}\right) = \underline{\quad 19 \quad}\ grams\ MgCl_2$$

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.

$$(5.00\ g\ Mg) \times \left(\frac{1\ mole\ Mg}{24.31\ g\ Mg}\right) \times \left(\frac{2\ moles\ Al}{3\ moles\ Mg}\right) \times \left(\frac{26.98\ g\ Al}{1\ mole\ Al}\right) = \underline{\quad 3.70 \quad}\ g\ Al$$

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**:

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

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.

$CaCl_2$ (aq) + Na_2CO_3 (aq) → $CaCO_3$ (s) + 2NaCl (aq)

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?

$$\left(2.00\ g\ CaCO_3\right) \times \left(\frac{1\ mole\ CaCO_3}{100.09\ g\ CaCO_3}\right) = 0.0200\ mol\ CaCO_3$$ *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?

$$\left(0.0200\ mol\ CaCO_3\right) \times \left(\frac{1\ mole\ CaCl_2}{1\ mole\ CaCO_3}\right) = 0.0200\ mol\ CaCl_2$$ *are needed to react*

$$\left(0.0200\ mol\ CaCl_2\right) \times \left(\frac{110.98\ g\ CaCl_2}{1\ mole\ CaCl_2}\right) = 2.22\ g\ CaCl_2$$ *are needed to react*

   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?

$$\left(0.0200\ mol\ CaCO_3\right) \times \left(\frac{1\ mole\ Na_2CO_3}{1\ mole\ CaCO_3}\right) = 0.0200\ mol\ Na_2CO_3$$ *are needed to react*

$$\left(0.0200\ mol\ Na_2CO_3\right) \times \left(\frac{105.99\ g\ Na_2CO_3}{1\ mole\ Na_2CO_3}\right) = 2.12\ g\ Na_2CO_3$$ *are needed to react*

   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?

$$\left(0.0200\ mol\ CaCO_3\right) \times \left(\frac{2\ mole\ NaCl}{1\ mole\ CaCO_3}\right) = 0.0400\ mol\ NaCl$$ *could be produced*

$$\left(0.0400\ mol\ NaCl\right) \times \left(\frac{58.44\ g\ NaCl}{1\ mole\ NaCl}\right) = 2.34\ g\ NaCl$$ *could be produced*

Table A: Predicted mass and moles of reactants and products

	Calcium chloride	Sodium carbonate	Calcium carbonate	Sodium chloride
Mole ratio (from balanced chemical equation)	*1*	*1*	*1*	*2*
Moles	*0.0200*	*0.0200*	*0.0200*	*0.0400*
Mass (grams)	*2.22*	*2.12*	**2.00**	*2.34*

Part 2: Collecting and analyzing reaction data

Students' data will vary somewhat. All mass data should be recorded to the maximum precision allowed by the balance, preferably to the hundredths place. It is important that students record the measured value from the balance, and not simply the calculated value, for the mass of each reactant.

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.

Student values will vary, depending on their actual yield values. Calculations should take the form:

$$percent\ yield\ =\ \left(\frac{actual\ yield}{2.00\ g\ CaCO_3}\right) \times\ 100\%$$

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

If a percent yield value is greater than 100%, this indicates that the actual mass of the material collected in the experiment is greater than the theoretical mass of the product predicted by stoichiometry.

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

If a percent yield value is less than 100%, this indicates that the actual mass of the material collected in the experiment is less than the theoretical mass of the product predicted by stoichiometry.

4. Consider your experimental procedure.

   a) What happened to the sodium chloride produced in this reaction?

   The sodium chloride produced in the reaction remained dissolved in water (aqueous), so it passed through the filter with the water and ended up in the collection beaker.

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

   It was necessary to rinse the solid product with water when it was in the filter to ensure that all of the sodium chloride passed through the filter and none of it stuck to the calcium carbonate.

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

   It was necessary to dry the product completely so that no water would be mixed in with the calcium carbonate.

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

   If the solid product is not rinsed sufficiently, then some sodium chloride could remain mixed in with calcium carbonate and add mass. If the solid product is not dried sufficiently, then some water will remain mixed in with calcium carbonate and add mass.

   e) What could lead to "lost" product mass?

   There are many possible sources of product loss that students could identify. Encourage them to think about the procedural steps, rather than focusing on "human error." Some good examples might include:

   - *When the reactants were transferred, some particles could stick to the sides of the weigh boat or the beaker.*
   - *When the reaction mixture was poured through the filter, some product particles could remain in the beaker or the funnel.*
   - *Some product particles might pass through or underneath the filter paper.*

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

> *Intentionally adding excess of one reactant can be useful to help ensure that the other (limiting) reactant reacts completely. This can increase the percent yield of the reaction.*

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

> *Students' responses will vary. Encourage students to consider aspects of the experimental design.*
>
> *Some examples might include:*
> - *Allowing the reaction to continue longer before filtering*
> - *Stirring the reaction more vigorously*
> - *Rinsing beakers with water to make sure all the reactants and/or products transfer completely*
> - *Rinsing the solid product more than three times*
> - *Drying the solid product for more time*

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 °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!*)

> $2H_2O\,(l) \rightarrow 2H_2\,(g) + O_2\,(g)$

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?

$$\left(2.50\ kg\ H_2O\right) \times \left(\frac{1000\ g}{1\ kg}\right) \times \left(\frac{1\ mole\ H_2O}{18.02\ g\ H_2O}\right) \times \left(\frac{1\ mole\ O_2}{2\ mole\ H_2O}\right) \times \left(\frac{32.00\ g\ O_2}{1\ mole\ O_2}\right) \times \left(\frac{1\ kg}{1000\ g}\right) = 2.22\ kg\ O_2$$

2.22 kg of oxygen gas theoretically can be produced each day by this method.

$$2.22\ kg\ \ O_2 \times \left(\frac{1\ person\ per\ day}{0.90\ kg\ \ O_2}\right) = 2.5\ people\ per\ day$$

This level of oxygen production could sustain 2 crew members each day. (And a 3rd for half a day!)

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

$LiClO_4$ (s) → LiCl (s) + 2O_2 (g)

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.)

$$\left(\frac{0.90\ kg\ \ O_2}{crew\ member\ per\ day}\right) \times (2\ days) \times (3\ crew\ members) = 5.4\ kg\ O_2$$ *would be needed*

$$\left(5.4\ kg\ O_2\right) \times \left(\frac{1000\ g}{1\ kg}\right) = 5400\ g\ O_2$$ *would be needed*

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

$$\left(5400\ g\ O_2\right) \times \left(\frac{1\ mole\ O_2}{32.00\ g\ O_2}\right) \times \left(\frac{1\ mole\ LiClO_4}{2\ mole\ O_2}\right) \times \left(\frac{106.39\ g\ LiClO_4}{1\ mole\ LiClO_4}\right) \times \left(\frac{1\ kg}{1000\ g}\right) = 9.0\ kg\ LiClO_4$$

They would need to decompose 9.0 kg of $LiClO_4$ to produce enough oxygen.

   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?

$$\left(9.0\ kg\ LiClO_4\right) \times \left(\frac{1\ candle}{2\ kg\ LiClO_4}\right) = 4.5\ candles$$

They would need to have at least 5 candles on board to generate enough oxygen to survive.

Keep creating!

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

Encourage students to think creatively and really put themselves in the mindset of being millions of miles from home in the far reaches of space without the possibility of receiving supplies from Earth. Encourage them to consider how their survival would depend on chemistry and the careful conservation of reactants and products in each reaction.

You might consider having students read an excerpt from The Martian *by Andy Weir or asking them to share their favorite books, TV shows, or movies where characters or real people use science to survive in inhospitable places.*