RATE OF DECOMPOSITION OF CALCIUM CARBONATE

AP* Chemistry
Unit 5 - Kinetics

Introduction

Why do some chemical reactions occur rapidly while others proceed more slowly? Understanding reaction rates is essential in fields such as chemistry, environmental science, and even art conservation. For example, marble statues from ancient civilizations gradually erode as acid rain reacts with the calcium carbonate in the stone—a process driven by the rate of the chemical reaction.

In this lab, you will investigate the rate of decomposition of calcium carbonate when it reacts with hydrochloric acid. By testing different acid concentrations, you will explore the principles of chemical kinetics and determine how various factors influence the speed of a reaction.

Concepts

- Reaction Rates
- Introduction to Rate Law
- Concentration Changes Over Time
- Elementary Reactions

Background

Calcium carbonate ($CaCO_3$) is a common mineral found in limestone, marble, seashells, and bedrock, making up over 4% of the Earth's crust. It has been used in construction for thousands of years, from ancient monuments like the Parthenon to modern buildings. However, calcium carbonate reacts with acids, leading to the gradual breakdown of materials such as marble and limestone. This process plays a key role in environmental issues like acid rain and ocean acidification.

In acidic solutions, calcium carbonate reacts with hydrochloric acid (HCl) to form calcium chloride ($CaCl_2$) and carbonic acid (H_2CO_3) (**Equation 1**). Carbonic acid is unstable and quickly decomposes into carbon dioxide gas (CO_2) and water (**Equation 2**). The overall balanced reaction is shown in **Equation 3**:

$$CaCO_3(s) + 2HCl(aq) \rightarrow CaCl_2(aq) + H_2CO_3(aq) \quad \text{(Equation 1)}$$

$$H_2CO_3(aq) \rightarrow CO_2(g) + H_2O(l) \quad \text{(Equation 2)}$$

$$CaCO_3(s) + 2HCl(aq) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l) \quad \text{(Equation 3)}$$

The speed of this reaction is studied through chemical kinetics, which examines how quickly chemical reactions occur. In this lab, you will measure the rate of the reaction by collecting and analyzing the volume or mass of CO_2 gas produced over time.

Reaction rates are influenced by several factors, including reactant concentration, temperature, surface area, and the presence of a catalyst. This investigation will focus on how the concentration of HCl affects the reaction rate.

Chemists describe this relationship using a mathematical expression called a rate law. For a general reaction A + B → products, the rate law is written as:

Rate = $k[A]^n[B]^m$ (**Equation 4**)

In **Equation 4**, *k* is the rate constant, and *n* and *m* represent the reaction orders with respect to each reactant. These exponents indicate how changes in concentration affect the reaction rate and must be determined experimentally. In this lab, you will gain a deeper understanding of reaction rates and how concentration influences them by studying how CO_2 production changes with different HCl concentrations.

Experiment Overview

In this lab, you will study the reaction rate of calcium carbonate with hydrochloric acid, which produces carbon dioxide gas. After an introductory activity to observe and measure gas production, you will design your own experiment to test how acid concentration affects the rate.

Working in groups, you will collect data on mass loss and gas volume over time, then analyze it to find the initial rate and determine the rate law of the reaction. If time permits, you may also explore how temperature or particle size affects the reaction rate.

Prelab Questions

1. In the reaction between solid calcium carbonate and hydrochloric acid, the rate law is:

   Rate = $k[HCl]^n$

   Why is calcium carbonate not included in the rate law?

2. In Step 4 of the Introductory Activity, why is it important to open the stopcock and quickly replace the stopper and syringe after adding HCl to the marble chips?

3. The rate of reaction between hydrogen peroxide and iodide ions was measured for three different initial concentrations of hydrogen peroxide. Based on the data, what is the order of the reaction with respect to hydrogen peroxide? Provide the reasoning that justifies your answer.

Concentration of H_2O_2 (M)	Average Initial Rate (M/s)
0.089	1.6×10^{-5}
0.044	7.2×10^{-6}
0.022	3.5×10^{-6}

Materials

Solutions & Chemicals

Calcium carbonate (marble chips), $CaCO_3$, 3–5 g
Hydrochloric acid solution, HCl, 6 M, 10 mL
Hydrochloric acid solution, HCl, 4 M, 10–20 mL
Hydrochloric acid solution, HCl, 2 M, 10–20 mL
Hydrochloric acid solution, HCl, 1 M, 10–20 mL
Silicone grease or petroleum jelly (optional)
Water, distilled or deionized

Equipment & Supplies

Balance, 0.001 g precision (shared)
Beakers, 100 mL or 150 mL, 3
Buret clamp
Erlenmeyer flasks, 125 mL, 3
Gas collection apparatus
- Stopcock
- Stopper, one-hole (to fit flask)
- Syringe, 120 mL
- Syringe adapter

Graduated cylinders, 10 mL and 25 mL
Mortar and pestle
Support stand
Timer or stopwatch
Wash bottle

Safety

Hazard	Precaution
Hydrochloric acid (HCl) – Corrosive to skin and eyes; toxic by inhalation or skin contact.	Avoid contact with eyes and skin. Wear chemical splash goggles, chemical-resistant gloves, and a chemical-resistant apron or lab coat. Clean up all spills immediately. Do not exceed 6 M concentration.
Calcium carbonate ($CaCO_3$) – Reacts with acid to release carbon dioxide gas.	Use no more than 0.4 g in gas collection experiments. Handle with care while wearing personal protective equipment.

Introductory Activity

Read the full procedure before starting. This activity can be done individually or as a class demo to encourage participation and discussion.

Set Up Apparatus

1. Assemble the gas collection setup (see **Figure 1**). Make sure the rubber stopper fits tightly and the stopcock is open.

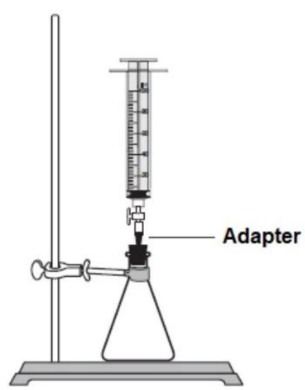


Figure 1. Gas collection apparatus.

Measure Marble Chips

2. Weigh about 0.4 g of calcium carbonate (roughly 3 marble chips) and place them in a 125 mL Erlenmeyer flask.

Measure Acid

3. Use a 10-mL graduated cylinder to measure 10 mL of 6 M hydrochloric acid.

Add Acid and Start Timer

4. Remove the stopper and syringe, quickly add the acid to the flask, then immediately reseal the flask and begin timing.

Observe Gas Collection

5. Watch as the syringe plunger rises while gas collects.

Record Volume Over Time

6. Measure the volume of gas in the syringe every minute for 10 minutes. To reduce resistance, gently press and release the plunger before each reading.

Graph Your Data

7. Plot the volume of CO_2 gas (mL) on the y-axis versus time (minutes) on the x-axis.

Guided Inquiry Activity

Discuss the Graph

1. Look at your graph showing the volume of CO_2 gas over time. Does the graph go up at a steady rate or start to level off? Use what you know about how the amount of HCl affects the speed of the reaction to explain the shape of the graph. Make sure your explanation connects what you see in the graph to what's happening in the reaction.

Estimate the Initial Rate

2. Use the slope of the linear portion of your CO_2 vs. time graph to estimate the initial rate of the reaction in mL/min. Show your calculations and use proper units and significant figures.

Find Limiting Reactant

3. Based on your measurements, calculate how many moles of $CaCO_3$ and HCl you used. Use this to figure out which one is the limiting reactant. Then, apply the ideal gas law ($PV = nRT$) to estimate how much CO_2 gas (in mL) should be produced. Be sure to use the correct units and show all your steps clearly, including your final answer with proper significant figures.

Evaluate Syringe Capacity

4. Can the syringe hold all the CO_2 produced? Calculate the percent of the reaction completed after 10 minutes. Consider possible sources of error.

Compare Methods

5. You have two ways to compare reaction rates: gas volume (Introductory Activity) or mass loss over time. For the mass loss method, how would the system's mass change? What measurement reflects the amount of CO_2 produced?

Choose Reactant Mass

6. Use stoichiometry to figure out how much CO_2 gas (in grams) would be produced from (a) 0.40 g and (b) 0.80 g of $CaCO_3$. Which amount is better for measuring mass loss during the reaction? Think about how accurate the balance is and how much HCl you would need for each.

Identify Key Variables

7. List the measurements needed to study how HCl concentration affects the reaction rate. Identify the independent and dependent variables, and choose appropriate HCl concentrations to test.

Control Surface Area

8. How could the size of the marble chips affect your results? What is the best way to keep surface area consistent between trials?

Write Two Procedures

9. Write step-by-step procedures for both the gas volume and mass loss methods. Include materials, glassware, equipment, safety precautions, and specific amounts and concentrations.

Review Other Variables

10. List other factors that could affect accuracy or consistency. Think about temperature, timing, measurement techniques, etc.

Run the Experiment

11. Perform the experiment and record your data in a well-organized table.

Analyze the Results

12. Make a graph for each trial showing how the volume of CO_2 (in mL) or the mass of CO_2 (in g) changes over time. Use your graphs to find the initial rate of the reaction for each HCl concentration.
13. Use your data from both the gas collection and mass loss methods to make graphs of initial reaction rate vs. HCl concentration. Use your graphs to figure out the reaction order with respect to HCl.
14. Compare your results from the gas collection and mass loss methods. If there are differences, explain why that might have happened. Think about possible errors or things that could have affected your results in each method.

Opportunities for Inquiry

If time allows, explore how other factors—like temperature, particle size, surface area, or a catalyst—affect the reaction rate between calcium carbonate and hydrochloric acid.

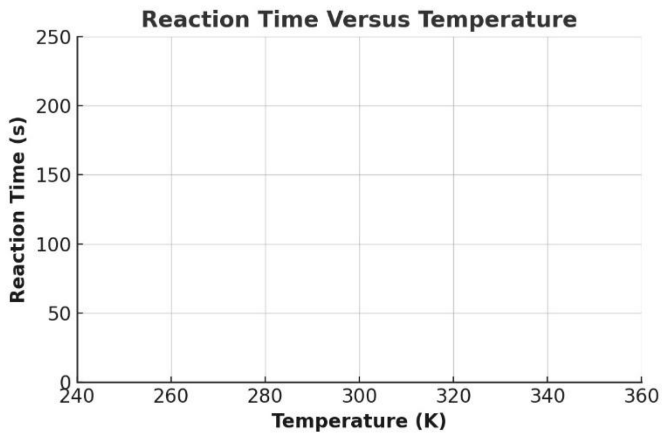
Post-Lab Exam Connect Questions

1. A 0.030 g piece of magnesium ribbon was reacted with 1 M hydrochloric acid at four different temperatures. The time for the magnesium to fully dissolve was recorded at each temperature.

Temperature (°C)	2	23	40	53
Average Reaction Time (s)	204	73	56	41
Average Reaction Rate (moles/s)				

a. Calculate the moles of magnesium that reacted and the average reaction rate (in mol/s) for each temperature.

b. Convert each temperature from °C to kelvins (K). Then, make a graph that shows how reaction time changes with temperature. Use your graph to predict how long the reaction would take at 75 °C.



c. Why is it better to use the Kelvin scale instead of Celsius when studying how temperature affects reaction rates? Use what you know about particle motion and collisions to explain.

d. Based on your results, does increasing the temperature affect how fast the reaction happens? Explain your answer using ideas from collision theory.

2. Consider the following experimental conditions for a kinetics experiment:

- **i.** Adding a catalyst
- **ii.** Increasing the concentration of the reactants
- **iii.** Decreasing the temperature
- **iv.** Increasing the surface area of a reactant

Which of these could slow down the rate of a reaction? Which would speed up the rate of reaction? Explain your reasoning.

3. Solid $CaCO_3$ undergoes endothermic decomposition in a sealed container according to this equilibrium reaction:

$$CaCO_3(s) \rightleftharpoons CaO(s) + CO_2(g), \quad K = [CO_2]$$

Which of the following changes would increase the magnitude of the equilibrium constant, K?

- **a.** Increasing the temperature of the system
- **b.** Removing some $CaCO_3$ at constant temperature
- **c.** Adding some $CaCO_3$ at constant temperature
- **d.** Removing CO_2 from the system at constant temperature as it forms

4. The rate law for a reaction is: rate = $k[Y]^0$. Which graph would give you a straight line?

- **a.** [Y] vs. time
- **b.** 1/[Y] vs. time
- **c.** ln[Y] vs. time
- **d.** [Y] vs. 1/time

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TEACHER NOTES

2024 Course and Exam Description Alignment Table

LO 5.1.A - Explain the relationship between the rate of a chemical reaction and experimental parameters.

Lab Section (Page #)	Skill(s)	How the Skill Is Executed in the Lab	Visual Cue
Prelab Questions *(p. 3)* Question 3	**5.F** – Calculate, estimate, or predict an unknown quantity from known quantities by selecting and following a logical computational pathway and attending to precision (e.g., performing dimensional analysis and attending to significant figures). **6.D** – Provide reasoning to justify a claim using chemical principles or laws, or using mathematical justification.	Students justify claims about reaction rate laws and calculate reaction order from data.	**5.F, 6.D**
Introductory Activity (*p. 5*) Graph Your Data	**3.A** – Represent chemical phenomena using appropriate graphing techniques, including correct scale and units.	Students measure CO_2 gas volume over time and create a graph with proper axes, units, and scale, visually representing the reaction progress.	**3.A**
Guided-Inquiry Activity (*p. 5*) Discuss the Graph	**6.F** – Explain the connection between experimental results and chemical concepts, processes, or theories.	Students analyze the graph of CO_2 volume vs. time and explain how changes in HCl concentration affect the reaction rate. The prompt helps students connect the graph shape to underlying chemical processes	**6.F**

LO 5.1.A - Explain the relationship between the rate of a chemical reaction and experimental parameters.

Lab Section (Page #)	Skill(s)	How the Skill Is Executed in the Lab	Visual Cue
Guided-Inquiry Activity (*p. 5*) Estimate the Initial Rate	**5.F** – Calculate, estimate, or predict an unknown quantity from known quantities by selecting and following a logical computational pathway and attending to precision (e.g., performing dimensional analysis and attending to significant figures).	Students calculate the initial rate from a graph by determining slope, applying units, and reasoning about rate behavior.	**5.F**
Guided-Inquiry Activity (*p. 5*) Find Limiting Reactant		Students calculate moles of reactants, identify the limiting reactant, and use the ideal gas law (PV = nRT) to predict CO_2 volume	
Guided-Inquiry Activity (*p. 6*) Choose Reactant Mass		Students use stoichiometry to calculate the theoretical mass of CO_2 produced from different amounts of $CaCO_3$, then evaluate which is better based on precision and volume of HCl needed—demonstrating logical quantitative reasoning and attention to accuracy.	
Guided-Inquiry Activity (*p. 6–7*) Analyze the Results	**3.A** – Represent chemical phenomena using appropriate graphing techniques, including correct scale and units. **5.A** – Represent chemical phenomena using appropriate graphing techniques, including correct scale and units. **6.G** – Explain how potential sources of experimental error may affect the experimental results.	Students create graphs to represent chemical changes over time, using correct units and axes (Skill 3.A), and identify quantities from the graph (like rate) needed to evaluate how concentration affects reaction rate (Skill 5.A). Students compare results between two experimental approaches and explain differences by identifying possible sources of experimental error, demonstrating their understanding of how error can affect results as described in Skill 6.G.	**3.A, 5.A, 6.G**

LO 5.1.A - Explain the relationship between the rate of a chemical reaction and experimental parameters.			
Lab Section (Page #)	**Skill(s)**	**How the Skill Is Executed in the Lab**	**Visual Cue**
Post-Lab Exam Connect Questions (*p. 7*) Question 1a	**5.F** – Calculate, estimate, or predict an unknown quantity from known quantities by selecting and following a logical computational pathway and attending to precision (e.g., performing dimensional analysis and attending to significant figures).	Students use experimental data to calculate moles of magnesium reacted and determine average reaction rate for each temperature using rate = moles/time.	**5.F**
Post-Lab Exam Connect Questions (*p. 7*) Question 1b	**3.A** – Represent chemical phenomena using appropriate graphing techniques, including correct scale and units.	Students convert temperatures to the correct units (kelvins) and graph reaction time versus temperature using appropriate axes, scale, and units.	**3.A**
Post-Lab Exam Connect Questions (*p. 8*) Question 1c	**6.D** – Provide reasoning to justify a claim using chemical principles or laws, or using mathematical justification.	Students justify the use of the Kelvin temperature scale by applying kinetic molecular theory and collision theory to explain why Kelvin gives a more accurate view of how temperature affects particle behavior and reaction rates—supporting claims using chemical principles.	**6.D**
Post-Lab Exam Connect Questions *(p. 8)* Question 1d	**6.F** – Explain the connection between experimental results and chemical concepts, processes, or theories.	Students connect observed changes in reaction time at different temperatures to the predictions made by collision theory. This task supports Skill 6.F by asking students to explain how their experimental data supports or challenges chemical theory.	**6.F**

Preparation

Materials Included in Kit (for 12 groups of students working in pairs)

Calcium carbonate (marble chips), $CaCO_3$, 70 g
Hydrochloric acid solution, HCl, 6 M, 500 mL*
Hydrochloric acid solution, HCl, 2 M, 500 mL
Hydrochloric acid solution, HCl, 1 M, 500 mL
Gas collection apparatus sets
- Stopcocks, plastic, with Luer lock, 6
- Stoppers, one-hole, rubber, size 5, 6
- Syringes, with Luer lock, 120 mL, 6
- Syringe extenders or adapters, 6

Dilute for student use. See Prelab Preparation

Additional Materials Required (for each lab group)

Water, distilled or deionized
Balance, 0.001-g precision (shared)
Beakers, 100 mL or 150 mL, 3
Buret clamp
Erlenmeyer flasks, 125 mL, 3
Graduated cylinders, 10 mL and 25 mL
Mortar and pestle (shared)
Silicone grease or petroleum jelly (optional)
Support stand
Timer or stopwatch
Wash bottle

For use with a colorimeter

Additional Materials Required for Prelab Preparation

Bottles to store solutions
Flask, volumetric or Erlenmeyer, 250 mL
Graduated cylinder, 250 mL
Magnetic stirrer and stir bar

Time Required

This lab takes two 50-minute class periods. After the Introductory Activity, your class will work in groups to design two alternative procedures during the guided-inquiry phase. Each group will be assigned one of the two procedures—half the class will perform one method, and the other half will perform the second. All procedures must be approved for safety before you begin. Make sure to complete the Prelab Questions before Day 1.

Prelab Preparation

Preparing 4 M Hydrochloric Acid Solution

To make 250 mL of 4 M HCl, dilute 167 mL of 6 M hydrochloric acid with distilled or deionized water to a final volume of 250 mL. Always add acid to water, not the other way around, and mix thoroughly before dispensing.

Safety Precautions

Hydrochloric acid is corrosive to skin and eyes and toxic by inhalation. Avoid contact with skin or eyes and keep an acid neutralizer nearby. Students must wear goggles, chemical-resistant gloves, and an apron or lab coat.

Use no more than 0.4 g of $CaCO_3$ per gas collection experiment, and keep HCl concentrations at or below 6 M. Remind students to wash hands before leaving. Follow all lab safety protocols and consult the SDS for handling and disposal info.

Disposal

Before beginning, review your current *Flinn Scientific Catalog and Reference Manual* for general safety and disposal procedures, and ensure compliance with all federal, state, and local regulations.

- Leftover reaction mixtures and excess HCl can be neutralized using a base following Flinn Disposal Method #24b, or excess HCl may be stored for future use.
- Unused solid calcium carbonate (marble chips) can be disposed of in the landfill according to Flinn Disposal Method #26a.

Teacher Guidance

Lab Hints

- To reduce friction in the syringe, apply a small amount of silicone grease or petroleum jelly to the black rubber gasket of the plunger.
- This lab supports key learning objectives on rate laws and interpreting experimental data. Comparing two experimental methods in the guided-inquiry part of the lab helps reinforce data analysis and evaluation skills.
- Encourage students to discuss the ideal number of concentration values and trials. At least three HCl concentrations should be tested. More trials (at different or the same concentrations) help improve reliability through averaging.
- Students may confuse reaction time with reaction rate. A helpful analogy is car travel—time to complete a trip versus speed. This can clarify the concept even if individual rates vary.
- To isolate concentration effects, students must control other variables. In the Introductory Activity, 10 mL of 6 M HCl provides 0.060 mol HCl. Since only 0.008 mol is consumed, this is about 13%, which exceeds the typical 5–10% range used in initial rate methods. At lower

acid concentrations, this issue is more significant. Students should consider using more solvent to keep HCl concentration more consistent (but not more $CaCO_3$).

- This inquiry-based lab can be extended to explore other variables like surface area or temperature. Do not use acid concentrations > 2 M or temperatures above 50 °C for these extensions.

Annotated Procedure

Introductory Activity

Read the full procedure before starting. This activity can be done individually or as a class demo to encourage participation and discussion.

Set Up Apparatus

1. Assemble the gas collection setup (see **Figure 1**). Make sure the rubber stopper fits tightly and the stopcock is open.

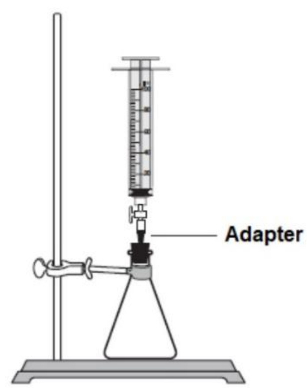


Figure 1. Gas collection apparatus.

Measure Marble Chips

2. Weigh about 0.4 g of calcium carbonate (roughly 3 marble chips) and place them in a 125 mL Erlenmeyer flask.

Measure Acid

3. Use a 10 mL graduated cylinder to measure 10 mL of 6 M hydrochloric acid.

Add Acid and Start Timer

4. Remove the stopper and syringe, quickly add the acid to the flask, then immediately reseal the flask and begin timing.

Observe Gas Collection

5. Watch as the syringe plunger rises while gas collects.

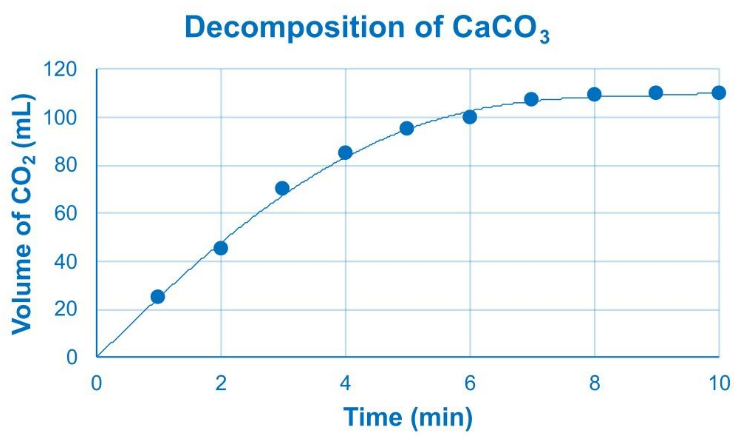
Record Volume Over Time

6. Measure the volume of gas in the syringe every minute for 10 minutes. To reduce resistance, gently press and release the plunger before each reading.

Graph Your Data

7. **3.A** Plot the volume of CO_2 gas (mL) on the y-axis versus time (minutes) on the x-axis.

Sample Data



Guided Inquiry Activity

Discuss the Graph

1. **6.F** Look at your graph showing the volume of CO_2 gas over time. Does the graph go up at a steady rate or start to level off? Use what you know about how the amount of HCl affects the speed of the reaction to explain the shape of the graph. Make sure your explanation connects what you see in the graph to what's happening in the reaction.

   Initially, the volume of CO_2 increases rapidly and linearly, indicating a constant reaction rate during the early stages. This linear region reflects a high concentration of reactants, where the rate remains relatively steady. Around the four-minute mark (depending on the trial), the curve begins to level off as the concentration of reactants decreases. Since reaction rate is directly related to reactant concentration, the rate slows as more reactants are consumed, resulting in the observed plateau in the graph

Estimate the Initial Rate

2. **5.F** Use the slope of the linear portion of your CO_2 vs. time graph to estimate the initial rate of the reaction in mL/min. Show your calculations and use proper units and significant figures.

   The initial reaction rate was approximately 25 mL of CO_2 per minute (25 mL/min), based on the average of two trials. The reaction proceeded very rapidly with 6 M HCl, which may have caused significant CO_2 loss during the short delay between adding the acid and sealing the gas collection apparatus.

Find Limiting Reactant

3. **5.F** Based on your measurements, calculate how many moles of $CaCO_3$ and HCl you used. Use this to figure out which one is the limiting reactant. Then, apply the ideal gas law (PV = nRT) to estimate how much CO_2 gas (in mL) should be produced. Be sure to use the correct units and show all your steps clearly, including your final answer with proper significant figures.

   The molar mass of $CaCO_3$ is 100.0869 g/mol. Given 0.40 g of $CaCO_3$:

   Moles of $CaCO_3$ = 0.40 g ÷ 100.0869 g/mol = 4.0×10^{-3} mol

   For 10.0 mL of 6 M HCl:

   Moles of HCl = 6 mol/L × 0.0100 L = 6×10^{-2} mol

   From the balanced equation:

   $$CaCO_3 + 2\ HCl \rightarrow CaCl_2 + CO_2 + H_2O$$

   The mole ratio is 1 mol $CaCO_3$: 1 mol CO_2

Since HCl is in excess, $CaCO_3$ is the limiting reactant, and the theoretical moles of CO_2 produced = moles of $CaCO_3$ = 4.0×10^{-3} mol

Using the ideal gas law (PV = nRT) to find volume at 295 K (22 °C) and 0.974 atm (740 mm Hg):

$V = (nRT) / P$
$= (4.0 \times 10^{-3} \text{ mol})(0.08206 \text{ L·atm/mol·K})(295 \text{ K}) \div 0.974 \text{ atm}$
$= 0.09927 \text{ L} \approx 99 \text{ mL}$

Theoretical volume of CO_2 = 99 mL

Evaluate Syringe Capacity

4. Can the syringe hold all the CO_2 produced? Calculate the percent of the reaction completed after 10 minutes. Consider possible sources of error.

The syringe volume exceeded the theoretical yield of CO_2, allowing complete gas collection in principle. After 10 minutes, the average reaction completion was approximately 90%, indicating some CO_2 was not captured. This loss may be due to CO_2 dissolving in the aqueous reaction mixture or escaping to the atmosphere during the brief delay between acid addition and sealing the gas collection system. Because the reaction proceeds very rapidly with 6 M HCl, this source of error is expected to be less significant at lower acid concentrations, where the reaction occurs more slowly.

Compare Methods

5. You have two ways to compare reaction rates: gas volume (Introductory Activity) or mass loss over time. For the mass loss method, how would the system's mass change? What measurement reflects the amount of CO_2 produced?

The mass of the reaction mixture—assumed to be the combined mass of $CaCO_3$ and added HCl—will decrease over time as CO_2 gas escapes to the atmosphere. The difference between the initial mass and the mass at any given time corresponds to the mass of CO_2 produced, since all other products remain in the container. A graph of mass loss versus time should resemble the CO_2 volume curve from the Introductory Activity, and the initial reaction rate can be determined from the slope of the linear portion of the curve.

Choose Reactant Mass

6. **5.F** Use stoichiometry to figure out how much CO_2 gas (in grams) would be produced from (a) 0.40 g and (b) 0.80 g of $CaCO_3$. Which amount is better for measuring mass loss during the reaction? Think about how accurate the balance is and how much HCl you would need for each.

   The molar mass of CO_2 is 44 g/mol. If 0.40 g of $CaCO_3$ is used, the theoretical yield is 4×10^{-3} moles of CO_2, resulting in a predicted mass loss of 0.18 g. If 0.80 g of $CaCO_3$ is used, the theoretical yield doubles to 8×10^{-3} mol, with a predicted mass loss of 0.35 g.

   Using 0.80 g of $CaCO_3$ and 20 mL of HCl is the better choice when using a 0.01-g precision balance, as the larger mass loss will be easier to detect—especially in the early part of the reaction, which is used to determine the initial rate. For improved accuracy, a 0.001-g balance is recommended.

Identify Key Variables

7. List the measurements needed to study how HCl concentration affects the reaction rate. Identify the independent and dependent variables, and choose appropriate HCl concentrations to test.

   Reaction rates are determined from the slope of the linear portion of a graph of CO_2 produced versus time. CO_2 can be measured either by volume (gas collection method) or by mass loss (open-flask method).

   When determining the reaction order with respect to HCl, the concentration of HCl is the independent variable, and the amount of CO_2 produced is the dependent variable. Suggested HCl concentrations include 1, 2, 3, and 4 M. Reactions with 6 M HCl tend to proceed too quickly and often give unreliable or inconsistent results. While 1 M HCl may react slowly, it only needs to be monitored through 10–20% completion to determine the initial rate.

   If using the mass loss method, it is essential to accurately determine the mass of HCl added. We recommend weighing the graduated cylinder plus acid before and after transferring the acid to the reaction flask to ensure precise measurements.

Control Surface Area

8. How could the size of the marble chips affect your results? What is the best way to keep surface area consistent between trials?

   Marble chips vary in both size and mass, making it difficult to maintain consistency across trials. Since the surface area of a solid significantly affects the rate of a heterogeneous reaction, it is essential to control this variable when investigating the effect of HCl concentration. One way to standardize surface area is to grind the marble chips into a fine powder using a mortar and pestle, thoroughly mix the powder in a vial, and then use measured samples from the same batch for each trial.

Write Two Procedures

9. Write step-by-step procedures for both the gas volume and mass loss methods. Include materials, glassware, equipment, safety precautions, and specific amounts and concentrations.

   The gas volume method used here is the same procedure outlined in the Introductory Activity.

Mass Loss Method: Step-by-Step Procedure

Measure Equipment

1. Record the mass of the empty 125 mL Erlenmeyer flask and the empty graduated cylinder. Enter these values in your data table.

Prepare the Reactants

2. Add 0.80 g of ground or powdered calcium carbonate to the Erlenmeyer flask. Record the total mass of the flask plus $CaCO_3$.
3. Measure 20.0 mL of 1 M HCl using the graduated cylinder. Record the mass of the graduated cylinder plus acid.

Start the Reaction

4. Quickly pour the HCl into the flask. Immediately place the flask on the balance and start timing without delay.

Collect Data

5. Record the mass of the flask and contents every 15 or 30 seconds for at least 3 minutes, or until the mass stops changing significantly. Enter all values in your data table.

Measure Graduated Cylinder (Post-Reaction)

6. After all mass measurements are complete, record the mass of the empty graduated cylinder to determine the actual mass of acid added.

Repeat with Other Acid Concentrations

7. Repeat Steps 1–6 using 2 M and then 4 M HCl, following the same procedure for each trial.

Graph and Analyze

8. Plot mass loss vs. time for each trial. Determine the initial reaction rate by calculating the slope of the linear portion of each graph (typically during the first 10–30% of the reaction).

Review Other Variables

10. List other factors that could affect accuracy or consistency. Think about temperature, timing, measurement techniques, etc.

Reaction rates are sensitive to temperature, so any fluctuations during the experiment can affect results. Maintaining a consistent temperature is important. Accurate timing is also essential, since both gas volume (gas collection method) and mass loss (mass loss method) are measured over time. Even small timing errors can impact calculated rates.

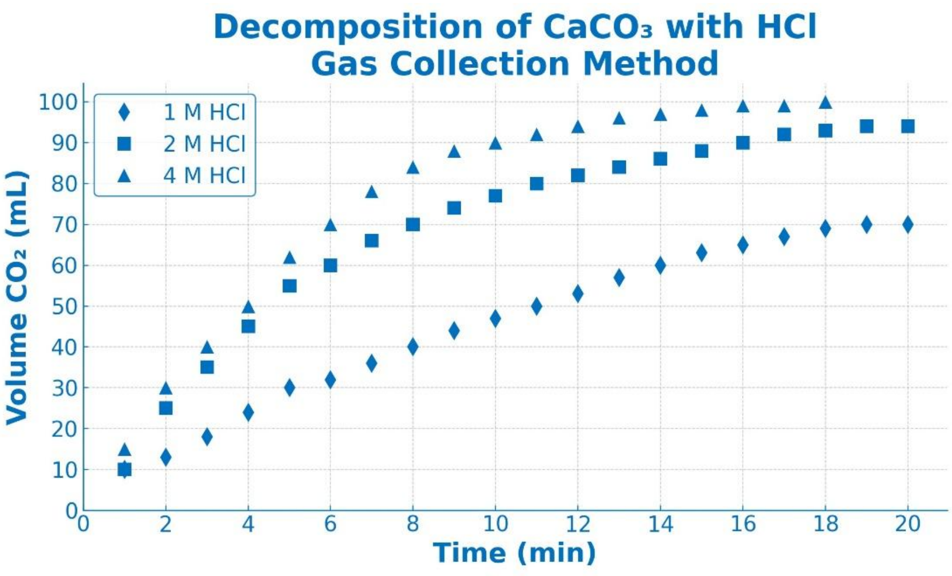
Each method has practical limitations. In the gas collection method, a syringe that is too small may not capture all the CO_2, leading to underreported values. A syringe that is too large can reduce measurement precision for small volumes, especially early in the reaction. In the mass loss method, a low-precision balance may not detect small but meaningful changes in mass. Choosing appropriate equipment and maintaining controlled conditions are key to generating accurate, consistent data.

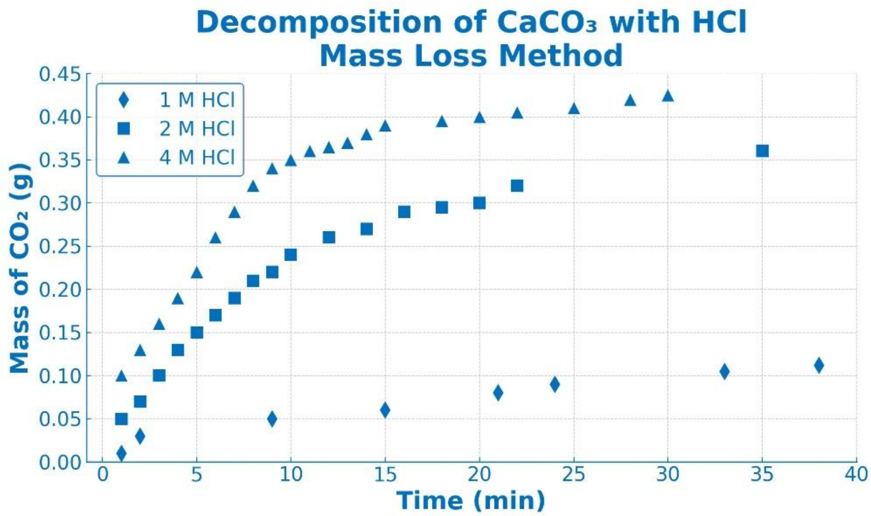
Run the Experiment

11. Perform the experiment and record your data in a well-organized table.

Analyze the Results

12. 3.A, 5.A Make a graph for each trial showing how the volume of CO_2 (in mL) or the mass of CO_2 (in g) changes over time. Use your graphs to find the initial rate of the reaction for each HCl concentration.

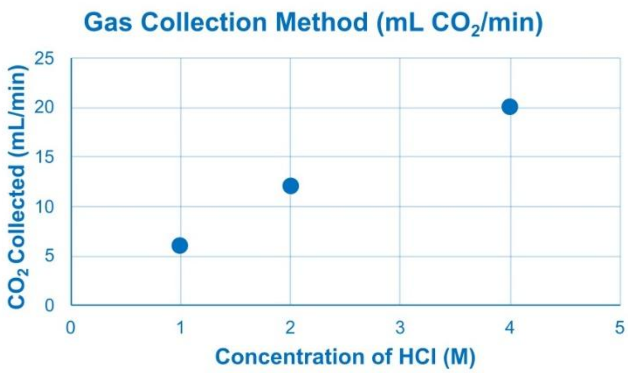


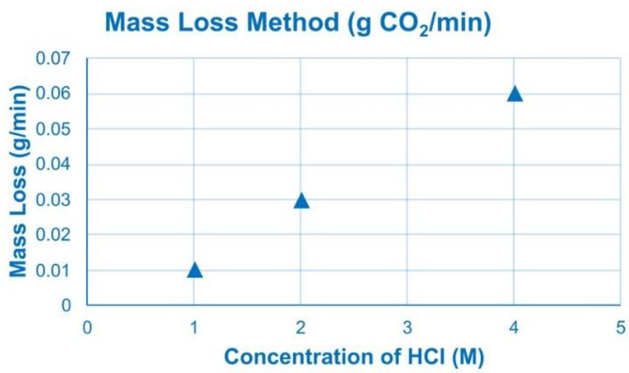


Concentration of HCl (M)	Initial Rate	
	Gas Collection Method (mL CO_2/min)	Mass Loss Method (g CO_2/min)
1	6	0.01
2	12	0.03
4	20	0.06

13. **3.A, 5.A** Use your data from both the gas collection and mass loss methods to make graphs of initial reaction rate vs. HCl concentration. Use your graphs to figure out the reaction order with respect to HCl.

The graphs from both the gas collection and mass loss methods show that the initial reaction rate increases roughly in direct proportion to the HCl concentration. This suggests the reaction is first order with respect to HCl.





14. **6.G** Compare your results from the gas collection and mass loss methods. If there are differences, explain why that might have happened. Think about possible errors or things that could have affected your results in each method.

The rate of calcium carbonate decomposition in hydrochloric acid depends on the HCl concentration. Two methods were used to compare rates: the gas collection method (0.40 g $CaCO_3$ with 10.0 mL HCl) and the mass loss method (0.80 g $CaCO_3$ with 20.0 mL HCl). Accurate measurement of the HCl mass was especially important in the mass loss trials. Reactions were run with 1 M, 2 M, and 4 M HCl.

Rates were determined using the method of initial rates, based on the slope of the linear portion of each curve (typically within the first 3 minutes or 10–30% completion). Both methods gave similar results, suggesting the rate is roughly proportional to HCl concentration, consistent with a first-order reaction, though more trials are needed to confirm this.

Each method showed strengths and limitations. The gas collection method was more consistent at lower concentrations (1 M, 2 M), likely due to slower, more controllable gas release. The mass loss method worked better at higher concentrations (2 M, 4 M). At 4 M, gas was likely lost during the delay between acid addition and sealing the system in the gas collection setup. At 1 M, mass changes were too small for a 0.001-g balance to detect accurately, limiting the method's usefulness at low rates.

Opportunities for Inquiry

If time allows, explore how other factors—like temperature, particle size, surface area, or a catalyst—affect the reaction rate between calcium carbonate and hydrochloric acid.

Answers to Prelab Questions and Post-lab AP Chemistry Connect Questions

Prelab Questions

1. In the reaction between solid calcium carbonate and hydrochloric acid, the rate law is:

   Rate = k[HCl]^n

   Why is calcium carbonate not included in the rate law?

   The concentration of a pure solid is equal to its density divided by its molar mass. This value is constant and does not depend on how much of the solid is present. Since the concentration of a solid does not change during a reaction, it is treated as a constant and does not appear in rate laws or equilibrium expressions.

2. In Step 4 of the Introductory Activity, why is it important to open the stopcock and quickly replace the stopper and syringe after adding HCl to the marble chips?

   When acid is added to calcium carbonate, CO_2 gas forms immediately. If the flask is not stoppered right away, gas will escape, making volume measurements inaccurate. The stopcock must be open before sealing the system. If gas builds up in a closed system, pressure can force the stopper or syringe to pop off, potentially spraying corrosive HCl.

3. **5.F, 6.D** The rate of reaction between hydrogen peroxide and iodide ions was measured for three different initial concentrations of hydrogen peroxide. Based on the data, what is the order of the reaction with respect to hydrogen peroxide? Provide the reasoning that justifies your answer.

Concentration of H_2O_2 (M)	Average Initial Rate (M/s)
0.089	1.6×10^{-5}
0.044	7.2×10^{-6}
0.022	3.5×10^{-6}

   Doubling the reactant concentration from 0.022 M to 0.044 M resulted in a doubling of the reaction rate, which supports a first-order relationship in the rate law. This conclusion is confirmed by a second comparison: increasing the concentration from 0.044 M to 0.089 M again doubled the rate.

Post-Lab Exam Connect Questions

1. A 0.030 g piece of magnesium ribbon was reacted with 1 M hydrochloric acid at four different temperatures. The time for the magnesium to fully dissolve was recorded at each temperature.

Temperature (°C)	2	23	40	53
Average Reaction Time (s)	204	73	56	41
Average Reaction Rate (moles/s)	5.9×10^{-6}	1.6×10^{-5}	2.1×10^{-5}	2.9×10^{-5}

a. **5.F** Calculate the moles of magnesium that reacted and the average reaction rate (in mol/s) for each temperature.

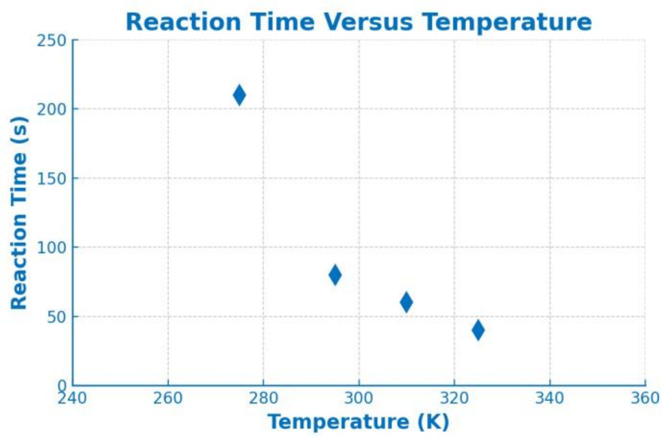
Moles of Mg reacted = 0.030 g ÷ 24.3 g/mole = 1.2×10^{-3} moles

Sample calculation for average reaction rate at 2 °C: 1.2×10^{-3} moles ÷ 204 s

= 5.9×10^{-6} moles/s

b. **3.A** Convert each temperature from °C to kelvins (K). Then, make a graph that shows how reaction time changes with temperature. Use your graph to predict how long the reaction would take at 75 °C.

At 75 °C = 348 K, the predicted reaction time would be very fast, perhaps about 10 seconds.



c. 6.D Why is it better to use the Kelvin scale instead of Celsius when studying how temperature affects reaction rates? Use what you know about particle motion and collisions to explain.

Kelvin is the better temperature scale for studying reaction rates because kinetic energy is directly proportional to temperature in kelvins. This relationship does not hold with the Celsius scale.

d. 6.F Based on your results, does increasing the temperature affect how fast the reaction happens? Explain your answer using ideas from collision theory.

According to collision theory, increasing the temperature raises the kinetic energy of molecules. This results in more frequent collisions and more molecules with enough energy to overcome the activation energy, which increases the reaction rate.

2. Consider the following experimental conditions for a kinetics experiment:

i. Adding a catalyst
ii. Increasing the concentration of the reactants
iii. Decreasing the temperature
iv. Increasing the surface area of a reactant

Which of these could slow down the rate of a reaction? Which would speed up the rate of reaction? Explain your reasoning.

Adding a catalyst, increasing the concentration of the reactants, and increasing the surface area of a reactant are all experimental conditions that would cause the rate of a reaction to increase. On the other hand, decreasing the temperature would lead to a decrease in the number of collisions between reactants, thus lowering the number of successful collisions that could lead to the formation of products.

3. Solid $CaCO_3$ undergoes endothermic decomposition in a sealed container according to this equilibrium reaction:

$$CaCO_3(s) \rightleftharpoons CaO(s) + CO_2(g), \quad K = [CO_2]$$

Which of the following changes would increase the magnitude of the equilibrium constant, K?

a. Increasing the temperature of the system
b. Removing some $CaCO_3$ at constant temperature
c. Adding some $CaCO_3$ at constant temperature
d. Removing CO_2 from the system at constant temperature as it forms

4. Solid $CaCO_3$ undergoes endothermic decomposition in a sealed container according to this equilibrium reaction:

The rate law for a reaction is: rate = $k[Y]^0$. Which graph would give you a straight line?

a. [Y] vs. time
b. 1/[Y] vs. time
c. ln[Y] vs. time
d. [Y] vs. 1/time

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