Catalysed Decomposition of Hydrogen Peroxide

Three calibration curves and a stoichiometric prediction for the Reactivity Rocket Project

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Year 10 Chemistry · Reactivity Rocket Project · Phase 1 Lab 1

Abstract

This investigation measures the **rate of catalysed decomposition of hydrogen peroxide** using potassium permanganate as a catalyst:

$$2\ H_2O_{2\,(aq)} \xrightarrow{KMnO_4} 2\ H_2O_{(l)} + O_{2\,(g)}$$

Students produce three calibration curves — rate vs [**H O**], rate vs [**KMnO**], and rate vs **temperature** — by measuring the volume of oxygen gas evolved over time. The teacher then demonstrates the same reaction at **35 % H O** (school lab-stock concentration). Students predict the 35 % rate by extrapolating their 3 % and 6 % calibration line and reconcile their prediction against the teacher's measurement.

The Arrhenius plot from the temperature calibration yields an apparent activation energy that students compare with the literature value of **56 kJ/mol** for KMnO -catalysed peroxide decomposition.

Finally, students combine their measurements into a single **stoichiometric prediction**: at the measured 35 % H O decomposition rate, can a school-scale rig in principle supply the oxygen demand of a 0.5 g/min ethanol burn in the rocket-project test article?

Introduction

Why this experiment matters

Engineering context

This is **not** a generic rates lab. The same chemistry you measure here drove the *Walter rocket* (Germany, 1937), the Me 163 Komet interceptor, the Bell Rocket Belt, and the turbopump of the X-1 — the first aircraft to break the sound barrier. All used catalysed decomposition of high-strength hydrogen peroxide as their oxygen source.

Your measurements set the parameters for the Computational Engineering team's prediction sheet, which the Manufacturing team takes to the vendor for the copper engine.

Background — the chemistry

Hydrogen peroxide decomposes spontaneously into water and oxygen. Without a catalyst, the reaction is very slow at room temperature: a bottle of 3 % H O from a chemist lasts months. With a catalyst, the reaction is dramatically faster.

$$2\ \mathrm{H_2O_{2\,(aq)}} \longrightarrow 2\ \mathrm{H_2O_{(l)}} + \mathrm{O_{2\,(g)}} \quad \text{(uncatalysed, very slow)} \tag{1}$$

$$2\ \mathrm{H_2O_{2\,(aq)}} \xrightarrow{\mathrm{KMnO_4}} 2\ \mathrm{H_2O_{(l)}} + \mathrm{O_{2\,(g)}} \quad \text{(catalysed, fast)} \tag{2}$$

Potassium permanganate (KMnO) provides the manganese in the +7 oxidation state. The reaction with H O reduces it to Mn^2 in acidic conditions, or to MnO in neutral / slightly alkaline conditions. Either way, the manganese species is **regenerated** as the reaction proceeds — the defining feature of a catalyst.

Theory — rate, calibration, extrapolation

The **rate** of the reaction is the volume of oxygen produced per unit time at the start of the run, before significant H O is consumed:

$$\text{rate} = \left.\frac{dV_{\mathrm{O_2}}}{dt}\right|_{t\to 0} \quad \text{(initial rate)}$$

(3)

We measure this as the slope of the **first 30 seconds** of a gas-volume-vs-time graph.

A **calibration curve** maps how the rate changes when one variable is changed and the others are held constant. Three calibration curves together describe the reaction:

1. **Rate vs [H O]** — fix [KMnO] and T; vary peroxide concentration
2. **Rate vs [KMnO]** — fix [H O] and T; vary catalyst concentration
3. **Rate vs T** — fix [H O] and [KMnO]; vary temperature

From the third curve we can extract an **activation energy** by the Arrhenius relation:

$$\ln(\text{rate}) = -\frac{E_a}{R} \cdot \frac{1}{T} + \text{const}$$

(4)

A graph of ln(rate) on the y-axis against $1/T$ on the x-axis is a straight line of slope $-E_a/R$, where $R = 8.314$ J mol^{-1} K^{-1}.

Hypothesis

Hypothesis 1. If the concentration of hydrogen peroxide is doubled while the catalyst concentration and temperature are held constant, then the initial rate of oxygen evolution will approximately double, because the rate of a catalysed reaction is approximately first-order in the substrate when the catalyst is not saturated.

Hypothesis 2. Increasing the concentration of KMnO catalyst will *initially* increase the rate, but eventually the rate will plateau as the catalyst saturates the H O available, because rate is set by the limiting reactant once enough catalyst is present.

Hypothesis 3. Increasing the temperature by 10 °C will increase the rate by a factor of approximately two, because reactions with activation energies near 50 kJ/mol roughly double in rate per 10 °C (Arrhenius).

Materials and equipment

Per group (student rates calibration)

- 1 × 250 mL borosilicate Erlenmeyer (conical) flask
- 1 × pierced rubber stopper with delivery tube
- 1 × separating funnel (50 mL) with retort stand and clamp
- 1 × 100 mL inverted graduated cylinder over a water trough

- 1 × stopwatch (smartphone is fine)
- 1 × thermometer (0–100 °C) **or** K-type thermocouple
- 1 × 600 mL water bath beaker + hot plate (Experiment 3 only)
- 1 × labelled waste container ("KMnO / H O waste")
- Goggles + lab coat + nitrile gloves (NOT latex)
- **3 % H O** (chemist-grade) — 200 mL per group
- **6 % H O** (chemist-strong-grade) — 200 mL per group
- **KMnO solutions** at 0.05, 0.10, 0.20, 0.40 M — 50 mL of each per group
- Paper towels (spill clean-up — **water only**, never near peroxide)

Class (teacher 35 % H O demonstration)

- 1 × 250 mL borosilicate Erlenmeyer flask, fresh
- 1 × wide-bore inverted gas collection cylinder
- **35 % H O** — 50 mL aliquot, dispensed by teacher from oxidiser cabinet
- KMnO solution 0.10 M
- CO extinguisher within 3 m
- Eyewash within 3 m
- 2 m floor tape line for student observation distance
- Wide-bore separating funnel for catalyst delivery

Safety

The risk assessment for this experiment is rated **Medium Risk** by the laboratory technician. Five controls apply.

1. **35 % H O is dispensed by the teacher only.** Students never open the oxidiser cabinet, never handle the stock bottle, and never transfer 35 % material. Risk codes R-01, R-02, R-03 from the Reactivity Rocket Project safety case.
2. **No paper towels, gloves, rags, or organic fabric within 1 m of the 35 % rig.** Concentrated H O + organic = ignition risk. Spills are flushed with **water only**.
3. **Nitrile gloves only.** Latex degrades on contact with peroxide.
4. **Goggles always.** Splash from KMnO stains skin and clothing indelibly within seconds.
5. **Wait until the flask is cool to room temperature before decanting.** Hot peroxide solutions continue evolving gas. Touch the flask base with a gloved finger as the cool-down check.

Waste H O + KMnO solutions: dilute to 10 % strength with water in the labelled waste bottle. Do **not** drain spent KMnO until the lab technician has confirmed pH 6–8.

Method

Variables

Type	Variable	How it is controlled or measured
Independent (Exp. 1)	[H O]	3 % vs 6 % stock
Independent (Exp. 2)	[KMnO]	0.05, 0.10, 0.20, 0.40 M
Independent (Exp. 3)	Temperature	15, 25, 35, 45 °C (water bath)
Dependent	Initial rate of O evolution (mL / s)	Slope of first 30 s of gas-volume-vs-time graph
Controlled	Volume of H O aliquot	50 mL per run, measured by the same flask
Controlled	KMnO drip rate	1 drop per second (counted by recorder)
Controlled	Same balance, zeroed before each weighing	Tare to 0.00 g
Controlled	Same gas-collection cylinder, water level reset	Re-fill the trough between runs

Procedure — Experiment 1: rate vs [H O]

1. **Assemble the rig.** Clamp the Erlenmeyer flask in the fume cupboard. Connect the stoppered delivery tube to the inverted graduated cylinder over the water trough. Confirm the cylinder is filled with water and the meniscus is at the 0 mL line.
2. **Position the separating funnel.** Clamp it above the flask. Close the tap. Pour 50 mL of 0.10 M KMnO into the funnel.
3. **Pour the peroxide.** Carefully add **50 mL of 3 % H O** to the flask. Seal the stopper.
4. **Confirm zero.** Confirm the gas cylinder reads 0 mL.
5. **Start the run.** Open the funnel tap to deliver KMnO at exactly **1 drop per second**. Start the stopwatch when the *first drop* contacts the H O surface.
6. **Record.** At every **10 s** read the gas-volume on the cylinder. Continue for **180 s** or until the cylinder fills.
7. **Stop the catalyst.** Close the funnel tap. Continue recording until gas evolution slows to less than 1 mL per 10 s.
8. **Reset and repeat.** Decant the flask to the labelled waste container. Rinse the flask with water. Reset the gas cylinder.
9. **Run the second concentration.** Repeat steps 3–8 with **50 mL of 6 % H O** instead of 3 %.

10. **Run triplicates.** Each concentration should be run **three times**. The mean of the three initial-rate slopes is the calibration point for that concentration.

Procedure — Experiment 2: rate vs [KMnO]

Same procedure as Experiment 1, but:

1. Use **6 % H O** for every run.
2. Vary the **KMnO concentration** in the funnel through **0.05, 0.10, 0.20, 0.40 M** in successive runs.
3. Maintain 1 drop/s drip rate every time.
4. Three repeats per concentration.

Procedure — Experiment 3: rate vs temperature

Same procedure as Experiment 1, but:

1. Use **6 % H O** and **0.10 M KMnO** for every run.
2. Vary the **flask temperature** by standing it in a water bath at **15, 25, 35, 45 °C**.
3. Verify the flask + contents temperature with the thermometer or thermocouple *immediately* before starting the run.
4. Three repeats per temperature.

Teacher demonstration — 35 % H O

This portion is run by the teacher only. Students record from the 2 m line. Standard Operating Procedure **SOP-03** in the Reactivity Rocket Project safety case applies.

The teacher repeats the rig of Experiment 1 with **50 mL of 35 % H O** and **0.10 M KMnO** at 25 °C. The reaction is vigorous and produces hot steam plus oxygen. The Rocket Chemistry team's Recorder reads gas volume every **5 s** from the wide-bore cylinder. The teacher closes the funnel tap after 60 s of gas evolution.

Results

Raw data — Experiment 1: rate vs [H O]

Table 2: **Table 1.** Volume of oxygen collected at successive times for the two student-handled peroxide concentrations. Triplicates per concentration.

Time (s)	3 % run 1 (mL)	3 % run 2 (mL)	3 % run 3 (mL)	6 % run 1 (mL)	6 % run 2 (mL)	6 % run 3 (mL)
0	0	0	0	0	0	0
10						
20						
30						
60						
120						
180						

Table 3: **Table 2.** Calibration points for Experiment 1.

[H O] (% w/w)	Mean rate (mL/s) over 0–30 s	Standard deviation across triplicates
3 %		
6 %		

Raw data — Experiment 2: rate vs [KMnO]

Table 4: **Table 3.** Catalyst-saturation calibration data.

[KMnO] (M)	Mean rate (mL/s)	SD across triplicates
0.05		
0.10		
0.20		
0.40		

Raw data — Experiment 3: rate vs temperature

Table 5: **Table 4.** Arrhenius calibration data.

T (°C)	T (K)	1/T (K ^{1})	Mean rate (mL/s)	ln(rate)
15	288.15	0.003470		
25	298.15	0.003354		

T (°C)	T (K)	1/T (K ¹)	Mean rate (mL/s)	ln(rate)
35	308.15	0.003245		
45	318.15	0.003143		

Teacher demonstration result

Table 6: **Table 5.** Comparison of the teacher's 35 % H O measurement with the student team's extrapolation from the Experiment 1 calibration.

Quantity	Value
[H O]	35 % w/w
[KMnO]	0.10 M
Temperature	25 °C
Mean rate over 0–30 s (measured)	mL/s
Mean rate over 0–30 s (extrapolated from student 3 % + 6 % data)	mL/s
Residual (measured − extrapolated)	mL/s

Worked example

Demonstration data (made-up but reasonable for school equipment).

Experiment 1, 3 % H O trial 1: gas readings of 0, 4, 9, 14, 26, 47, 65 mL at 0, 10, 20, 30, 60, 120, 180 s. Initial slope (0–30 s):

$$\text{rate}_{3\%} = \frac{14 - 0}{30 - 0} = 0.47 \text{ mL/s}$$

(5)

Experiment 1, 6 % H O trial 1 gives a 30 s value of 32 mL:

$$\text{rate}_{6\%} = \frac{32 - 0}{30 - 0} = 1.07 \text{ mL/s}$$

(6)

The 6 % rate is about **2.3×** the 3 % rate. The expected ratio is **2.0×** if the reaction is first-order in H O . The measured 2.3× is within typical experimental scatter for a Year 10 rig — *consistent with first-order behaviour.*

Linear extrapolation through (0, 0), (3 %, 0.47), (6 %, 1.07) predicts a rate at 35 % of approximately:

$$\text{rate}_{35\%} \approx \frac{0.47 + 1.07}{2} \times \frac{35}{4.5} \approx 5.9 \text{ mL/s}$$

(7)

The teacher's measurement at 35 % should fall reasonably close to this value — perhaps ±30 % — given that linear extrapolation across a 10× concentration range is optimistic.

Observations

Record qualitative observations for each experiment.

Colour of the KMnO on contact with H O . *Does the purple disappear immediately? At what point during the run does fresh KMnO stop being decolourised?*

Bubbles in the flask. *Where do they form first? Top? Bottom? Where the drops land?*

Flask temperature. *Touch the flask base with a gloved finger during the run. Cool? Slightly warm? Genuinely hot? (35 % only — expect hot steam, do not touch.)*

Cylinder reading rhythm. *Does the gas rise smoothly or in pulses? Pulses suggest gas trapped under the stopper.*

Analysis

Computing initial rate from the time series

For each run, take the **first 30 seconds** of gas-volume data. Plot a small graph or use a calculator to find the best-fit slope. The slope is the **initial rate** in mL/s. Average across triplicates.

Why the first 30 s?

As the reaction proceeds, H O is consumed. The rate at t = 60 s is slower than the rate at t = 10 s because there is less peroxide left. We want the rate at the *start*, when the concentrations are still at their initial values — that is the rate that corresponds to the calibration point.

Drawing the three calibration curves

Plot:

- **Graph 1.** Mean rate (mL/s) on the y-axis vs [H O] (% w/w) on the x-axis. Two points so far; add the teacher's 35 % point. Draw the best fit through (0, 0) — three concentrations.
- **Graph 2.** Mean rate on the y-axis vs [KMnO] (M) on the x-axis. Four points. Look for a plateau.
- **Graph 3.** ln(rate) on the y-axis vs 1/T (K [1]) on the x-axis. Four points. Should be a straight line.

Extracting activation energy

From Graph 3, fit a line of best fit through the four points. The slope of the line is $-E_a/R$:

$$E_a = -\text{slope} \times R = -\text{slope} \times 8.314 \text{ J mol}^{-1}\text{K}^{-1}$$

(8)

The literature value for KMnO -catalysed H O decomposition is **56 kJ/mol**. Your measured value should fall within **40–70 kJ/mol** for the data to be considered consistent.

Stoichiometric prediction — the engineering question

Combine your measurements:

$$\dot{V}^{35\%}_{\text{O}_2,\text{measured}} = \text{? mL/min from teacher demonstration}$$

(9)

The ethanol burn in the rocket project's vendor test article is designed at **0.5 g/min** ethanol. The combustion reaction:

$$\text{C}_2\text{H}_5\text{OH} + 3\ \text{O}_2 \longrightarrow 2\ \text{CO}_2 + 3\ \text{H}_2\text{O}$$

(10)

Stoichiometric oxygen demand:

$$\dot{V}_{\text{O}_2,\text{demand}} = \frac{0.5 \text{ g/min}}{46.07 \text{ g/mol}} \times 3 \times 22.4 \text{ L/mol} = 0.73 \text{ L/min} = 730 \text{ mL/min}$$

(11)

Required 35 % H O flow rate at the *measured* decomposition rate is:

$$\dot{V}_{\mathrm{H_2O_2,required}} = \frac{730\ \mathrm{mL/min}}{\dot{V}_{\mathrm{O_2\ per\ mL\ of\ 35\ \%}}}$$

(12)

where the O yield per mL of 35 % H O is calculated from stoichiometry as **130 mL O per mL of 35 % solution** (working: 1 mL of 35 % at density 1.13 g/mL → 0.40 g H O → 0.012 mol → 0.006 mol O × 22.4 L/mol = 132 mL).

Decision rule for the engineering claim

If the required H O flow is **less than 20 mL/min**, the school-scale rig can plausibly supply the ethanol burn. If it is greater, the school chemistry cannot drive the burn and the vendor must use a different oxidiser source (compressed O from cylinder, LOX, or higher-grade peroxide). The Walter rocket of 1937 needed 80 % H O for exactly this reason.

Discussion

Did the data support the hypotheses?

For each hypothesis, follow the **Claim → Evidence → Reasoning** model.

Hypothesis 1 (rate vs [H O]). Is the 6 % rate approximately double the 3 % rate? Quote the ratio you measured and compare with the expected 2×.

Hypothesis 2 (rate vs [KMnO]). Did the rate plateau as catalyst concentration increased? At what catalyst concentration did the gain stop being proportional? Was the catalyst saturated at the 0.40 M condition?

Hypothesis 3 (rate vs T, Arrhenius). What activation energy did your slope give? Is it in the 40–70 kJ/mol range expected for KMnO -catalysed H O decomposition? If not, name the most likely source of the discrepancy.

The stoichiometric prediction. State whether your reconciliation shows the project's chemistry can in principle drive the ethanol burn, or whether the vendor will need a different oxidiser. Defend the answer with your computed required H O flow rate.

Sources of uncertainty

Drip rate variability

1 drop per second is a target, not a precise measurement. Drops vary in volume between 0.04 and 0.06 mL. A 50 % variation in catalyst delivery rate maps onto a 10–20 % rate uncertainty in the low-catalyst regime (before saturation).

Gas collection over water

Oxygen partially dissolves in water and the cylinder is not at STP. For typical lab conditions (~25 °C, 101 kPa) the dissolution and volume corrections are 2–5 % and partially cancel; we neglect them.

Self-heating during the run

The reaction is exothermic. Over a long run the flask warms slightly. For the 6 % student case this is < 3 °C and is below the temperature calibration sensitivity. For the 35 % teacher case it is dramatic — hot steam — and confounds the cool-flask Arrhenius extrapolation.

Linear extrapolation to 35 %

The 3 % and 6 % student points are extrapolated linearly to 35 % — a 10× extrapolation. Real-world rates can deviate from linearity at high concentration due to mass-transfer limitations on the catalyst surface. Expect the teacher's measured rate to fall below the linear extrapolation by 20–40 %.

Comparison with the rocket project

This experiment's data feeds two other documents.

1. The **Computational Engineering team's prediction sheet** — your Arrhenius activation energy parameterises the Rust crate's `arrhenius_extrapolate` function, and your stoichiometric flow calculation appears on the public viewer at https://pilot.mentormind.com.au/edu/chemistry-prep/year10/reactivity-rocket-project/computational-engineering-static-test.html
2. The **Manufacturing team's vendor RFQ** — your measurement of the 35 % decomposition rate sets the design oxidiser flow that the vendor's quote must match.

Your three calibration curves are not a textbook exercise — they set parameters that the rest of the project relies on.

Conclusion

State your conclusion in five sentences.

1. Restate whether rate increased with [H O], with [KMnO], and with temperature in the directions you predicted.
2. Quote your measured activation energy from the Arrhenius fit, with its uncertainty range, and compare to the literature value of approximately 56 kJ/mol.
3. State whether the teacher's 35 % measurement fell within the range your student extrapolation predicted, and name the source of any residual (likely linearity-breakdown, or self-heating).
4. State whether the required H O flow for a 0.5 g/min ethanol burn is feasible at school-scale (under 20 mL/min) or not.
5. Identify the largest source of uncertainty in your experiment and suggest one specific improvement that would reduce it.

Extension questions

Q1. Predict whether 80 % H O — the concentration used in the Walter rocket — would supply the O demand for a 5 g/min ethanol burn (10× larger than our school-scale design). Show working.

Q2. Suppose the Computational Engineering team's prediction sheet expects a peroxide decomposition rate of 6.5 mL O /s per mL of 35 % H O . Your measurement is 5.1 mL O /s per mL. Reconcile the difference: which of your sources of uncertainty (if any) could account for a 20 % under-measurement?

Q3. The Bell Rocket Belt used 90 % H O decomposed by a silver catalyst bed rather than KMnO in solution. Discuss why a solid catalyst bed is preferred at engine scale.

Q4. Sketch the rate-vs-[KMnO] graph for an *uncatalysed* and a catalysed reaction on the same axes. What would the y-axis intercept of the uncatalysed line tell you? Why does the catalysed line *not* start from zero on the x-axis?

Q5. The literature activation energy for *uncatalysed* H O decomposition is approximately 75 kJ/mol. The catalysed value is approximately 56 kJ/mol. What is the physical interpretation of the 20 kJ/mol difference?

References

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