

SL Chemistry Internal Assessment

Efficiency per unit mass of five different catalysts for hydrogen peroxide decomposition

Research question

Which catalyst out of Manganese (IV) Oxide, Lead (II, IV) Oxide, Potassium Iodide, Copper (II) Oxide, and Iron (III) Oxide will most effectively catalyze the decomposition of hydrogen peroxide per unit mass?

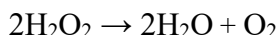
Introduction

Background

The “elephant’s toothpaste” is one of the first chemical experiments I witnessed as a kid. The reaction happens when high concentrations of hydrogen peroxide rapidly decays into oxygen gas and water in the presence of potassium iodide as a catalyst, where the rapid release of small oxygen bubbles from the solution causes a large volume foam to emerge. The research question originates from the thought that there could be a more effective catalyst than potassium iodide for the “elephant’s toothpaste” reaction.

Relevant Theory

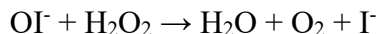
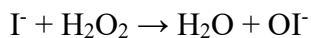
Hydrogen peroxide, H_2O_2 , is an unstable compound that spontaneously decays into water and oxygen through the equation:



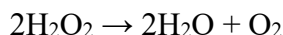
However, the spontaneous decay of hydrogen peroxide is relatively slow, with a half-life of 10-20 hours (*source*) in air. This makes spectacles such as the “elephant’s toothpaste” reaction impossible without a catalyst.

Catalysts are chemicals that increase the rate of certain reactions without undergoing any permanent chemical change itself. Illustrated on *Figure-1*, the presence of catalysts offer an alternative pathway to the reaction that requires an overall lower activation energy. With reference to the Maxwell-Boltzmann distribution on *Figure-2*, this statistically allows a higher proportion of the reactants to have enough energy to react, and hence increases the rate of reaction.

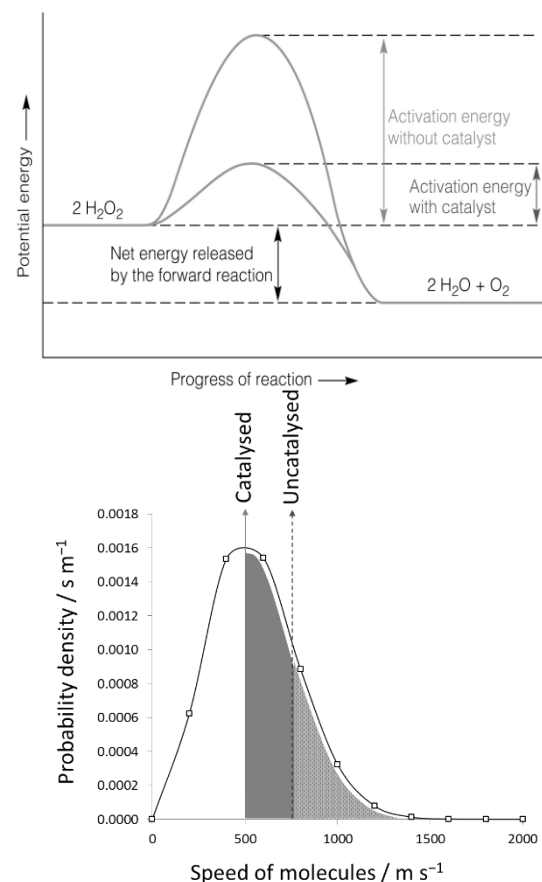
Most catalysts do undergo chemical change during the reaction they catalyze, but the chemical change is reversed after the reaction has finished. Potassium iodide as the catalyst used in the “elephant’s toothpaste” reaction is one such example, as can be seen from the following system of equations describing how potassium iodide catalyzes the decomposition of hydrogen peroxide:



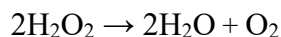
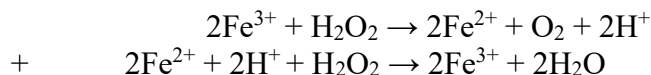
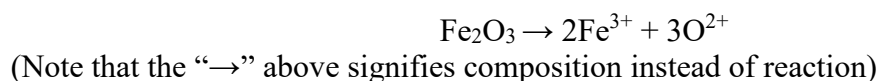
This shows that hydrogen peroxide initially acts as an oxidizing agent that oxidizes the dissociated iodide ions to hypoiodite ions, but it later acts as a reducing agent that reduces hypoiodite ions back to iodide ions. Adding the two conversion equations between iodide and hypoiodite together, the iodide and hypoiodite on each side of the equation cancels out to give just:



, which proves that potassium iodide is a catalyst of hydrogen peroxide decomposition, and quantitatively shows that 1 mol of potassium iodide will be able to decompose 2 mol of hydrogen peroxide per catalytic cycle.

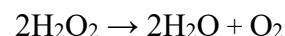
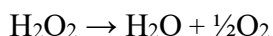
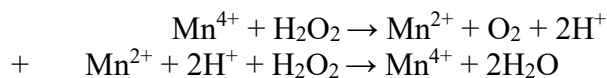
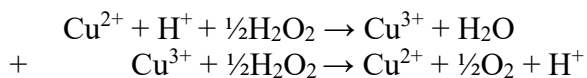


Besides potassium iodide, a number of transition metal oxides are also catalysts for hydrogen peroxide decomposition. Transition metals' ability to change between different oxidation states also allows catalytic cycles with hydrogen peroxide to occur. Take iron (III) oxide for example:



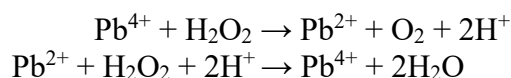
As shown, hydrogen peroxide can reduce Fe^{3+} to Fe^{2+} and also oxidize Fe^{2+} back to Fe^{3+} , which creates a catalytic cycle similar to that of potassium iodide, where 1 mol of iron (III) oxide is able to decompose 2 mol of hydrogen peroxide per catalytic cycle.

The catalytic cycle for copper (II) oxide and manganese (IV) oxide largely follow the same logic, which that:

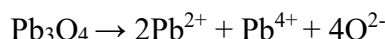


1 mol of copper (II) oxide is only able to decompose 1 mol of hydrogen peroxide per catalytic cycle, whereas 1 mol of manganese (IV) oxide will be able to 2 mol of hydrogen peroxide per catalytic cycle.

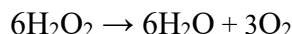
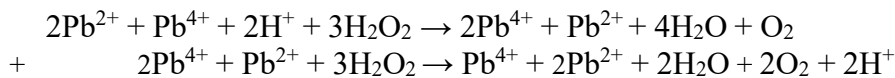
The same logic also applies lead (II, IV) oxide, but we have to realize that lead ions exists as both lead (II) and lead (IV) in this compound. The catalytic cycle between Pb^{2+} and Pb^{4+} are as below:



Given that:



, it can be deduced that the complete catalytic cycle for lead (II, IV) oxide is:



Hence, 1 mol of lead (II, IV) oxide will be able to decompose 6 mol of hydrogen peroxide per catalytic cycle.

Hypothesis (Rushed, will be further refined, please feedback on possible further developments)

There is substantial evidence to support that potassium iodide will be the most efficient catalyst out of all five in terms of catalyzing the decomposition of hydrogen peroxide.

With respect to the theory that catalysts provide a reaction pathway with lower activation energy, the efficiency of a catalyst should be determined by two factors.

The first factor is the activation energy of the catalyzed pathway, where the lower the activation energy, the more efficiently the catalyst will be able to catalyze the reaction as a higher proportion of reactants can react through this pathway. Looking back at all the equations of catalytic cycles in the previous section, it can be deduced that the catalytic cycle for all five catalysts involve an ion forming and breaking bonds with oxygen. Hence to estimate the activation energy, we can look at the bond dissociation energy of each ion with oxygen, where the lower the bond dissociation energy, the easier it will be to break or for a bond of the ion with oxygen, hence the catalytic cycle will require less energy to complete, leading to a lower activation energy. Out of all five catalysts, I-O covalent bonds have the lowest bond dissociation energy of 184 kJ mol^{-1} , whereas the bond dissociation energy for the other four transition metal oxides are above 300 kJ mol^{-1} due to the bond being ionic. Therefore from the perspective of activation energy, potassium iodide should be the most efficient catalyst. From the same respect, the least effective catalyst should be iron (III) oxide, as it has the highest bond dissociation energy.

The second factor deciding the efficiency of a catalyst is the probability of the reactants taking the catalyzed pathway, bearing in mind that a portion of the reactants still react following the original pathway even when the catalyst is present. The probability of the reactants taking the catalyzed pathway is largely dependent on the contact surface area between the reactants and the catalyst, where the larger the contact surface area of the catalyst, the more chance there will be for the reactants to interact with the catalyst and hence leading to a higher probability of the reactant taking the catalyzed pathway. While the four metal oxides are all insoluble in water and exists as solid suspensions, potassium iodide is soluble in water, making the contact surface area magnitudes higher than that of the metal oxides.

Relevant properties of each catalyst				
Catalyst	Molar mass (g mol^{-1})	Quantity of H_2O_2 decomposed per catalytic cycle per mol of catalyst	Bond dissociation energy (kJ mol^{-1})	Surface area (qualitative)
Manganese (IV) Oxide	86.94	2	402	Powdered
Lead (II, IV) Oxide	685.6	6	378	Powdered
Potassium Iodide	166.0	2	184	Dissolved
Copper (II) Oxide	79.55	1	343	Powdered
Iron (III) Oxide	159.7	2	409	Powdered
Red cells are maximum values Blue cells are minimum values				

Variables

Independent Variable	Definition	Catalysts
	Five different catalysts for hydrogen peroxide decomposition.	Manganese (IV) Oxide, MnO_2 Lead (II, IV) Oxide, Pb_3O_4 Potassium Iodide, KI Copper (II) Oxide, CuO Iron (III) Oxide, Fe_2O_3

Dependent Variable	Symbol	Definition	Proximate Variables		
	r_0	The instantaneous initial rate of reaction when the catalyst comes into contact with hydrogen peroxide. The instantaneous initial rate will be indicative a catalyst's efficiency at decomposing hydrogen peroxide ($\text{cm}^3 \text{s}^{-1}$).	Proximate independent variable	Symbol	Definition
				V	Volume of gas produced by the reacting system (cm^3)
			Proximate dependent variable	Symbol	Definition
				t	Time taken for the system to produce $V \text{ cm}^3$ of gas (seconds)

Controlled Variables	Symbol	Definition	Controlled Value	Reason for control
	m	Mass of the catalyst used	$1 \text{ gram} \pm 5\%$	The aim of this experiment is to determine the efficiency of each catalyst per unit mass.
	T_0	Initial temperature of the system	$21 \pm 5\%$	Initial temperature influences the initial rate of reaction independent of the catalyst used.
	A	Surface area of the catalyst	All catalysts used are powdered (unable to control quantitatively)	Surface area influences the initial rate of reaction independent of the catalyst used.
	$[\text{H}_2\text{O}_2]$	Concentration of hydrogen peroxide solution used in the experiment	$0.10 \pm 0.01 \text{ mol dm}^{-3}$	Concentration of hydrogen peroxide as a reactant influences the initial rate of reaction independent of the catalyst used.
	$V[\text{H}_2\text{O}_2]$	Volume of hydrogen peroxide solution used in the experiment	$200.0 \pm 0.2 \text{ cm}^3$ (Class B 200 cm^3 volumetric flask)	The volume hydrogen peroxide solution determines the length of time that the reaction is going to persist. Since time is measured as the independent variable, this variable should be kept constant.

Method

Chemicals and equipment list

List of chemicals		
Chemical	Quantity	Description
Manganese (IV) Oxide	5 grams	Solid, finely powdered
Lead (II, IV) Oxide	5 grams	Solid, finely powdered
Potassium Iodide	5 grams	Solid, finely powdered
Copper (II) Oxide	5 grams	Solid, finely powdered
Iron (III) Oxide	5 grams	Solid, finely powdered
1 mol dm ⁻³ Hydrogen Peroxide solution	500 cm ³	Assuming $\pm 1\%$ uncertainty of concentration
Distilled water	-	-

Safety precaution for hazardous chemical

Lead (II, IV) Oxide is labelled as very toxic for aquatic life with long lasting effects (hazard statement H410) and harmful if inhaled (hazard statement H332) by the GHS. therefore any liquid contaminated by the compound should be thoroughly filtered before going down the sink, while the powdered solid should be handled with care to prevent it from becoming air borne.

List of equipment		
Equipment	Quantity	Uncertainty
500 cm ³ Conical Flask	1	-
100 cm ³ beaker	2	-
Glass vial	5	-
Stop watch	1	± 0.01 seconds
Class B 20.00 cm ³ pipette and suction bulb	1	± 0.03 cm ³ ; $\pm 0.15\%$
Class B 200.0 cm ³ volumetric flask	1	± 0.2 cm ³ ; $\pm 0.08\%$
100 cm ³ Gas syringe with delivery tube and stopper	1	± 2.5 cm ³
Electronic Balance	1	± 0.0001 gram
Digital Thermometer	1	± 0.1 °C
Glass stirring rod	1	-
Molar and pestle	1	-
Clamp stand and clamp	1	-

Preparing diluted hydrogen peroxide solution

A test trial with manganese (IV) oxide shows that the reaction would be too rapid for any meaningful measurement to be taken using the requested 1 mol dm⁻³ hydrogen peroxide solution, hence the following steps are taken to prepare diluted hydrogen peroxide solutions on which meaningful measurements can be made.

1. A 20 cm³ aliquot of the 1 mol dm⁻³ is taken with the class B pipette and suction bulb, and transferred into the class B 200 cm³ volumetric flask.
2. The volumetric flask is filled with distilled water to the 200 cm³ mark.

The properties of diluted hydrogen peroxide solution prepared by this method is determined as follows:

$$\text{Original solution: } [\text{H}_2\text{O}_2] = \frac{1 \text{ mol} \pm 1\%}{1 \text{ dm}^3}$$

$$\text{During step 1: } n(\text{H}_2\text{O}_2) = \frac{1 \text{ mol} \pm 1\%}{1 \text{ dm}^3} \times (0.02 \text{ dm}^3 \pm 0.15\%)$$

$$n(\text{H}_2\text{O}_2) = 0.02 \text{ mol} \pm 1.15\%$$

$$\text{After step 2: } [\text{H}_2\text{O}_2] = \frac{0.02 \text{ mol} \pm 1.15\%}{0.2 \pm 0.08\%}$$

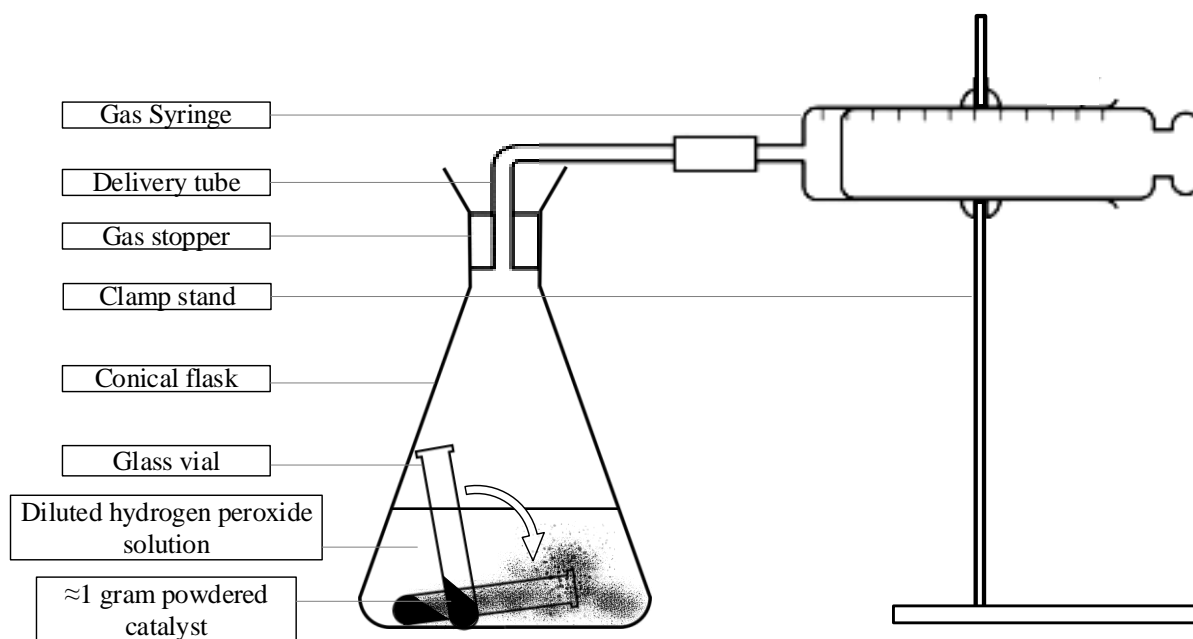
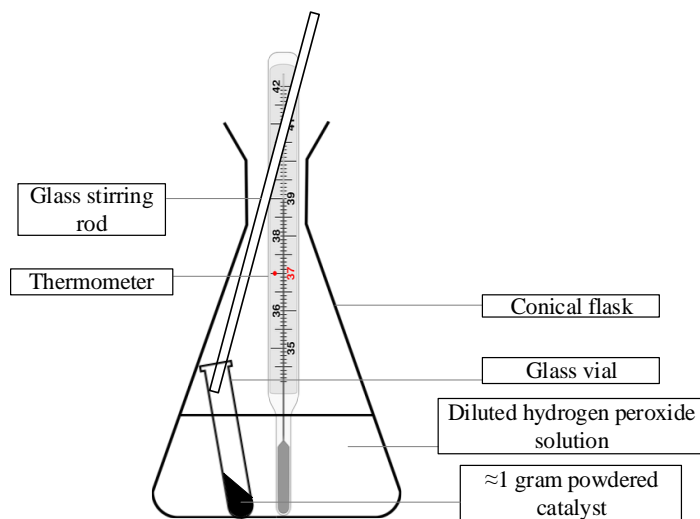
$$[\text{H}_2\text{O}_2] = 0.1 \text{ mol} \pm 1.23\%$$

$$[\text{H}_2\text{O}_2] = 0.10 \pm 0.01 \text{ mol dm}^{-3}$$

Experiment procedure

Repeat two trials of the following step for each of the five catalysts:

1. The catalyst should be grinded with a pestle and molar if it contains visible large pieces.
2. Measure and transfer $1 \text{ gram} \pm 5\%$ of the catalyst into a glass vial by using an electronic balance.
3. Transfer the prepared 200 cm^3 of $0.10 \pm 0.01 \text{ mol dm}^{-3}$ diluted hydrogen peroxide solution into the 500 cm^3 conical flask.
4. Carefully lower the glass vial containing the catalyst into the conical flask by using a glass stirring rod as shown in *Figure-__*, make sure the glass vial rests on the wall of the conical flask so that the catalyst does not come into contact with the solution.
5. Measure and record the temperature of the solution in the conical flask with a digital thermometer, note that the experiment should only proceed when the initial temperature of the solution is $21^\circ\text{C} \pm 5\%$.
6. Stopper the conical flask with a gas stopper connected to the gas syringe with a delivering tube as shown on *Figure-__*. Check to make sure that the system is airtight.
7. Shake the conical flask to let the glass vial to fall into the hydrogen peroxide solution as demonstrated on *Figure-__*, start timing on the stopwatch the moment that the catalyst is exposed to the solution.
8. Measure and record the time taken for the reacting system to produce 10 cm^3 , 20 cm^3 , 30 cm^3 , 40 cm^3 , 50 cm^3 , 60 cm^3 of gas.



Processing raw results

To evaluate the instantaneous initial rate r_0 of each reacting system, we must first be able to model the rate of reaction r as a function of time t from the raw measurements of t and V . The definition of rate of reaction r measured in terms of the volume of gas produced by a system is:

$$r = \frac{\Delta V}{\Delta t} \quad [1]$$

, hence it can be said that:

$$r = \frac{V_2 - V_1}{t_2 - t_1} \quad [2]$$

, where V_1 and V_2 are two consecutive volumes at which time is measured, while t_1 and t_2 are two consecutive measurements of time at V_1 and V_2 . It should be noted that [2] determines r as the average rate of reaction between the time interval $t_2 - t_1$. Hence if we are to assign a specific value of time to r , this value should be the average time t_μ of the interval, where:

$$t_\mu = \frac{t_2 - t_1}{2} \quad [3]$$

All raw data are processed using [2] and [3] to evaluate the behavior of the rate of reaction for each reacting system.

Treatment of errors and uncertainties

To account for both the uncertainty in repeated trials of measurement and the instrument error in individual measurements at the same time, an aggregate uncertainty is calculated for every trial average as follows:

$$\text{Aggregate error} = \frac{\text{Trial maximum} - \text{Trial minimum}}{2} + \sum \text{Instrument error}$$

, where each measured value's deviation from the average is added to the sum of the instrument error.

Aggregate error sample calculation: <i>Table-1</i> , raw data, Trial average = 32 ± 2 seconds	
Trial maximum = 34.11 seconds	Trial average = $\frac{34.11+30.62}{2} \pm \left(\frac{34.11-30.62}{2} + 0.01\right)$ seconds
Trial minimum = 30.62 seconds	Trial average = 32.365 ± 1.765 seconds
Total instrument error = ± 0.01	Trial average $\approx 32 \pm 2$ seconds

When uncertainties are propagated down into calculated values, the sum of the relative uncertainties associated with each value used in the calculation is taken, and then multiplied by the value of the result to give the propagated absolute error.

$$\text{Propagated error} = \sum \frac{\text{Associated error}}{\text{Value used in calculation}} \times \text{Calculated value}$$

Propagated error sample calculation: <i>Table-1</i> , processed data, $r = 0.3 \pm 0.2 \text{ cm}^3 \text{ s}^{-1}$	
$t_1 = 32 \pm 2$ seconds	$r = \frac{(61.1 \pm 0.4) - (32 \pm 2)}{(20.0 \pm 2.5) - (10.0 \pm 2.5)} \text{ cm}^3 \text{ s}^{-1}$
$t_2 = 61.1 \pm 0.4$ seconds	$r = \frac{29.1 \pm 8.25\%}{10 \pm 50\%} \text{ cm}^3 \text{ s}^{-1}$
$V_1 = 10.0 \pm 2.5 \text{ cm}^3$	$r = 0.291 \pm (0.291 \times 58.25\%) \text{ cm}^3 \text{ s}^{-1}$
$V_2 = 20.0 \pm 2.5 \text{ cm}^3$	$r \approx 0.3 \pm 0.2 \text{ cm}^3 \text{ s}^{-1}$

Experiment results

Table-1: Data and observations for Manganese (IV) Oxide

Initial conditions and controlled variables, with aggregate error		Raw data				Processed data	
Average initial temperature across trials (°C)	21.1 ±0.2	Volume of gas V (cm³) ± 2.5 cm³ instrument error	Time t (Seconds)			Average time t_{μ} (Seconds) with propagated error	Rate r (cm³ s⁻¹) with propagated error
			Trial 1	Trial 2	Trial average with aggregate error		
Average mass of catalyst across trials (grams)	1.019 ±0.003	10.0	34.11	30.62	32 ± 2	47 ± 3	0.3 ± 0.2
Volume of H₂O₂ solution (dm³)	200.0 ±0.6	20.0	60.72	61.45	61.1 ± 0.4	78 ± 2	0.29 ± 0.07
Concentration of H₂O₂ solution (mol dm⁻³)	0.10 ±0.01	30.0	96.78	93.29	95 ± 2	116 ± 5	0.24 ± 0.04
		40.0	133.92	140.63	137 ± 3	164 ± 6	0.19 ± 0.03
		50.0	193.05	188.23	191 ± 2	225 ± 4	0.15 ± 0.02
		60.0	260.47	256.87	259 ± 2		
Qualitative Observations							
<div><div>- Catalyst is a finely powdered black solid.</div><div>- Instant bubbling when the catalyst is released into the prepared H₂O₂ solution.</div><div>- Catalyst has poor solubility, mostly remaining solid in the solution as black suspensions.</div></div>							

Table-2: Data and observations for Lead (II, IV) Oxide

Initial conditions and controlled variables, with aggregate error		Raw data				Processed data	
		Volume of gas V (cm ³) ± 2.5 cm ³ instrument error	Time t (Seconds)			Average time t_{μ} (Seconds) with propagated error	Rate r (cm ³ s ⁻¹) with propagated error
			Trial 1	Trial 2	Trial average with aggregate error		
			± 0.01 seconds instrument error				
Average initial temperature across trials (°C)	21.2 ±0.1	10.0	5.82	6.25	6.0 ± 0.2	8.0 ± 0.5	3 ± 1
Average mass of catalyst across trials (grams)	1.016 ±0.002	20.0	10.27	9.78	10.0 ± 0.3	12 ± 1	1.9 ± 0.6
Volume of H ₂ O ₂ solution (dm ³)	200.0 ±0.6	30.0	15.61	13.42	15 ± 1	18 ± 2	1.7 ± 0.4
Concentration of H ₂ O ₂ solution (mol dm ⁻³)	0.10 ±0.01	40.0	21.52	22.63	22.1 ± 0.6	26 ± 2	1.5 ± 0.3
		50.0	28.13	30.22	29 ± 1	33 ± 2	1.4 ± 0.2
		60.0	35.09	37.56	36 ± 1		
Qualitative Observations							
<ul style="list-style-type: none">- Catalyst is a finely powdered, vividly orange solid.- Instant rapid bubbling when the catalyst is released into the prepared H₂O₂ solution.- Catalyst has poor solubility, mostly remaining solid in the solution as orange suspensions.							

Table-3: Data and observations for Potassium Iodide, where the system is left undisturbed

Initial conditions and controlled variables, with aggregate error		Raw data				Processed data	
Average initial temperature across trials (°C)	20.9 ±0.2	Volume of gas V (cm³) ± 2.5 cm³ instrument error	Time t (Seconds)			Average time t_{μ} (Seconds) with aggregate error	Rate r (cm³ s⁻¹) with propagated error
			Trial 1	Trial 2	Trial average with propagated error		
			± 0.01 seconds instrument error				
		10.0	30.63	32.67	32 ± 1		
		20.0	65.85	70.51	68 ± 2		
		30.0	103.59	108.92	106 ± 3		
Average mass of catalyst across trials (grams)	1.043 ±0.003	40.0	143.13	152.28	148 ± 5	48 ± 3	0.3 ± 0.1
		50.0	185.73	191.56	189 ± 3	85 ± 5	0.26 ± 0.07
		60.0	230.77	262.81	250 ± 20	123 ± 7	0.25 ± 0.05
						164 ± 8	0.23 ± 0.04
Volume of H₂O₂ solution (dm³)	200.0 ±0.6					210 ± 20	0.22 ± 0.04
Concentration of H₂O₂ solution (mol dm⁻³)	0.10 ±0.01						
Qualitative Observations							
<div><div>- Catalyst is a powdered crystalline white solid.</div><div>- The catalyst is highly soluble, the solid catalyst dissolves instantly when released into the prepared H₂O₂ solution, followed by bubbling.</div><div>- The originally clear and colourless H₂O₂ solution turns into a clear brown colour after the catalyst is dissolved in it.</div><div>- The reactive system is sensitive to motion, where disturbing the system leads to observably more rapid bubbling.</div></div>							

Table-4: Data and Observations for Copper (II) Oxide

Initial conditions and controlled variables, with aggregate error	
Average initial temperature across trials (°C)	20.8 ±0.1
Average mass of catalyst across trials (grams)	0.968 ±0.004
Volume of H ₂ O ₂ solution (dm ³)	200.0 ±0.6
Concentration of H ₂ O ₂ solution (mol dm ⁻³)	0.10 ±0.01

Raw data			
Volume of gas <i>V</i> (cm ³) ± 2.5 cm ³ instrument error	Time <i>t</i> (Seconds)		
	Trial 1 ± 0.01 seconds instrument error	Trial 2	Trial average with aggregate error
10.0	179.93	217.67	200 ± 20
20.0	444.61	482.19	460 ± 20
30.0	836.17	1004.02	920 ± 80
40.0	1351.71	1572.23	1500 ± 100
50.0	1942.11	2207.48	2100 ± 100
60.0	2662.65	2905.25	2800 ± 100

Processed data	
Average time <i>t</i> _μ (Seconds) with propagated error	Rate <i>r</i> (cm ³ s ⁻¹) with propagated error
330 ± 40	0.04 ± 0.02
690 ± 90	0.022 ± 0.007
1200 ± 200	0.018 ± 0.006
1800 ± 200	0.016 ± 0.004
2400 ± 300	0.014 ± 0.003

Qualitative Observations
<ul style="list-style-type: none">- Catalyst is a finely powdered black solid.- Instant rapid bubbling when the catalyst is released into the prepared H₂O₂ solution.- Catalyst has poor solubility, mostly remaining solid in the solution as black suspensions.

Table-5: Data and observations for Iron (III) Oxide

Initial conditions and controlled variables, with aggregate error		Attempts to collect data and qualitative observations			
Average initial temperature across trials (°C)	21.3 ± 0.2	<ul style="list-style-type: none"> - Catalyst is a finely powdered red solid. - No visual evidence of any reaction occurring after the catalyst is released into the prepared H₂O₂ solution initially, but tiny bubbles begin to emerge after around 600 seconds. - Catalyst has poor solubility, mostly remaining solid in the solution as red suspensions. - The amount of gas produced by the system in 1800 seconds is not measureable by the gas syringe used, no data could be collected on the prepared H₂O₂ solution as a result. - An attempt was made to use the undiluted 1 mol dm⁻³ H₂O₂ solution with the catalyst, but still yielded no measurable result after 1800 seconds, hence measurement for this catalyst is terminated. 			
Average mass of catalyst across trials (grams)	0.942 ± 0.002				
Volume of H ₂ O ₂ solution (dm ³)	200.0 ± 0.6				
Concentration of H ₂ O ₂ solution (mol dm ⁻³)	0.10 ± 0.01				

Table-6: Data and observations for Potassium Iodide, where the system is constantly swirled

Initial conditions and controlled variables, with aggregate error		Raw data				Processed data	
Average initial temperature across trials (°C)	21.1 ± 0.1	Volume of gas <i>V</i> (cm³) ± 2.5 cm³ instrument error	Time <i>t</i> (Seconds)			Average time <i>t</i> _μ (Seconds) with aggregate error	Rate <i>r</i> (cm³ s ⁻¹) with propagated error
			Trial 1	Trial 2	Trial average with aggregate error		
Average mass of catalyst across trials (grams)	1.012 ±	10.0	9.15	8.47	8.8 ± 0.4	13.9 ± 0.8	1.0 ± 0.4
Volume of H ₂ O ₂ solution (dm³)	200.0 ±0.6	20.0	19.34	18.76	19.1 ± 0.3	25 ± 1	0.91 ± 0.2
Concentration of H ₂ O ₂ solution (mol dm ⁻³)	0.10 ±0.01	30.0	31.17	29.02	30 ± 1	36 ± 3	0.8 ± 0.2
		40.0	43.68	40.21	42 ± 2	48 ± 4	0.8 ± 0.2
		50.0	56.72	52.64	55 ± 2	61 ± 2	0.8 ± 0.1
		60.0	67.33	67.22	67.28 ± 0.08		

Qualitative Observations	
<ul style="list-style-type: none">- Catalyst is a powdered crystalline white solid.- The catalyst is highly soluble, the solid catalyst dissolves instantly when released into the prepared H₂O₂ solution, followed by bubbling.- The originally clear and colourless H₂O₂ solution turns into a clear brown colour after the catalyst is dissolved in it.- Bubbling significantly intensifies after swirling begins.	

Figure-1: Relationship between the volume of gas produced V and time t for each catalyst reacting with the prepared H_2O_2 solution

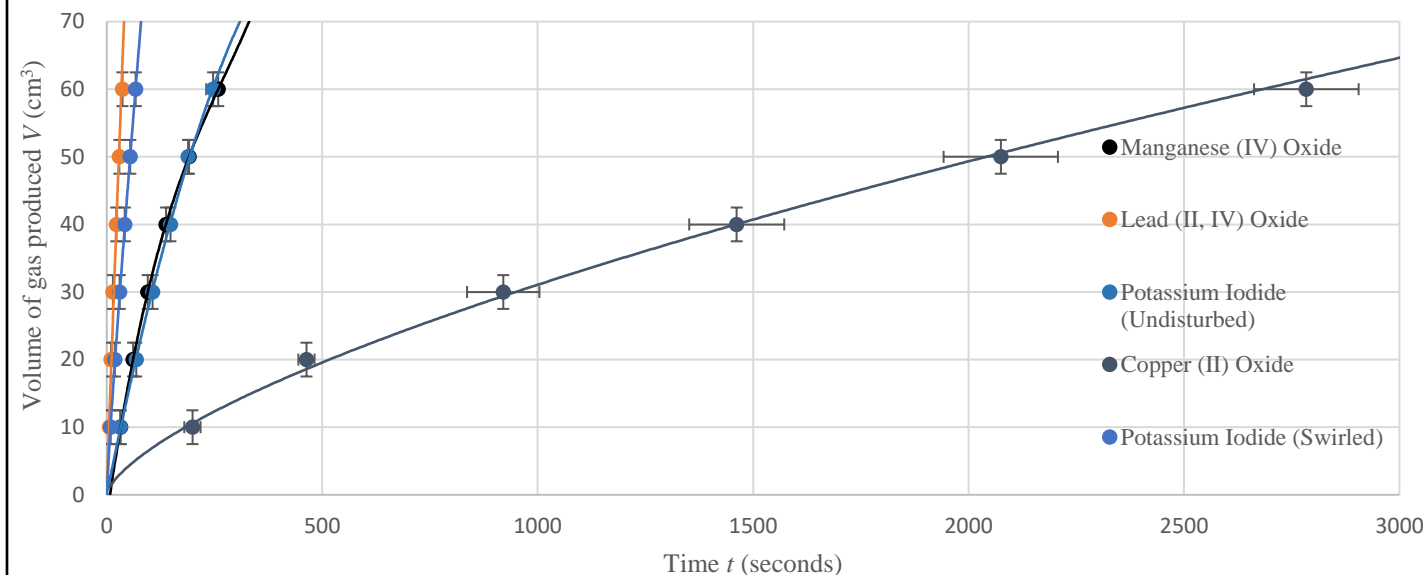
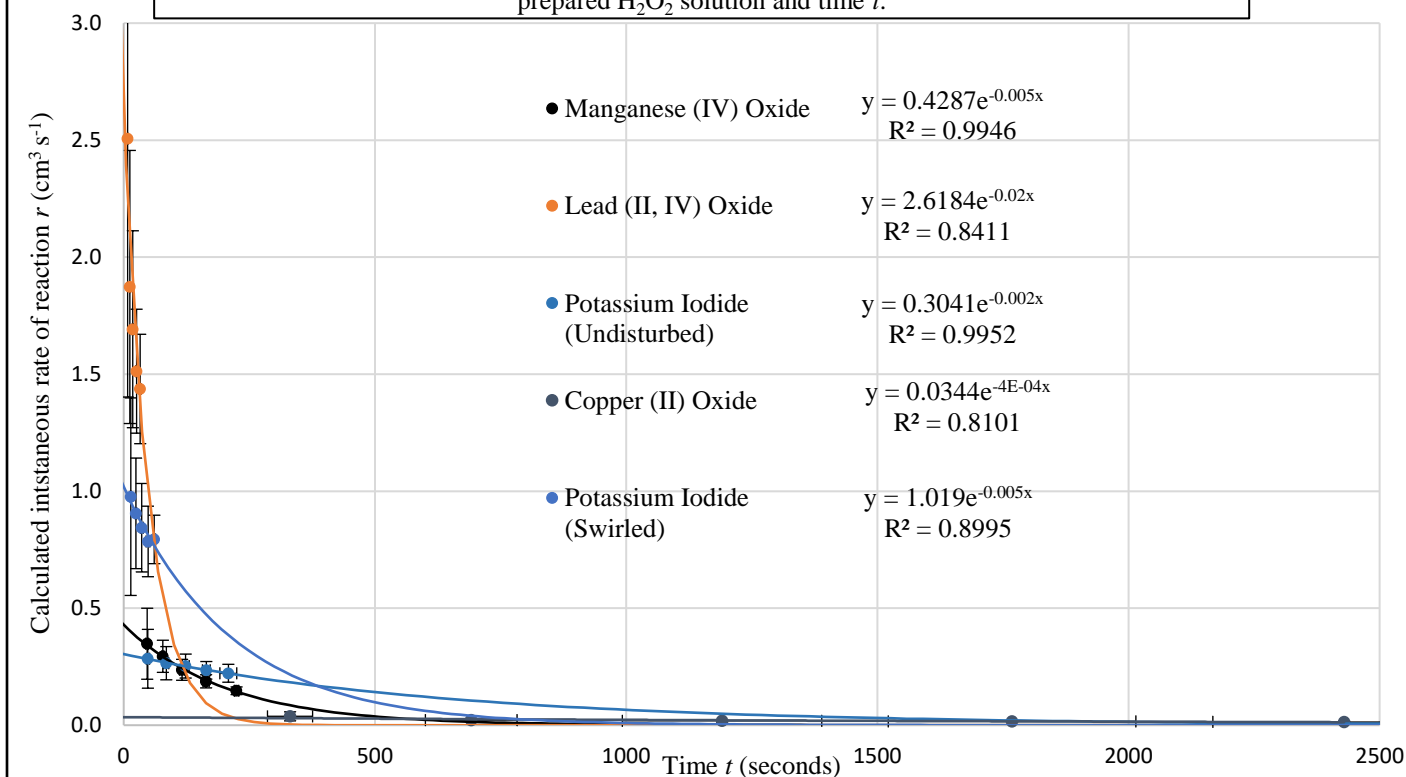


Figure-2: Relationship between the calculated rate of reaction r of each catalyst reacting with the the prepared H_2O_2 solution and time t .



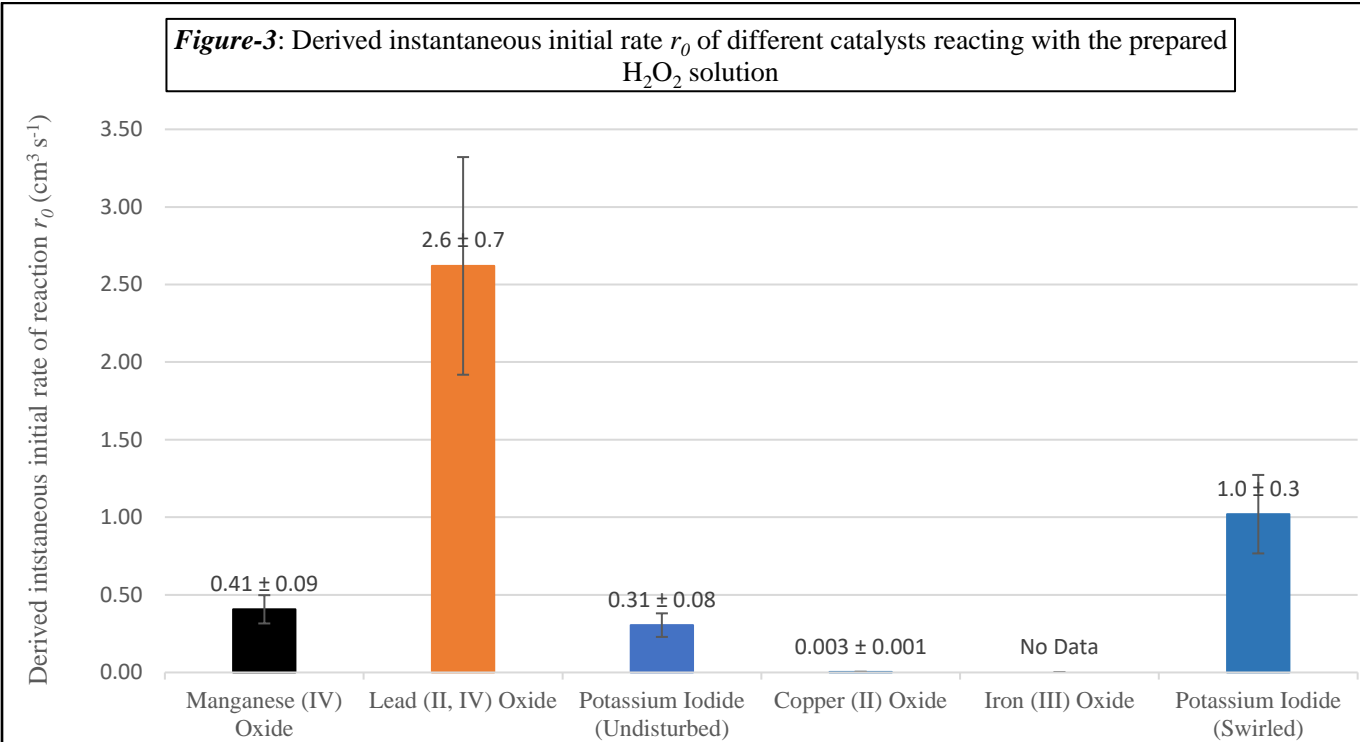
The relationship between the rate of reaction r with time t for each of the reacting system is modelled as an exponential decay, its formula being in the format of:

$$y = a e^{-k x}$$

, where a and k and real constants. Following this formula, the constant a is the y -intercept of the function, hence the a value of each equation on *Figure-2* is taken as r_0 of each reacting system. The uncertainty of the constant a is calculated by taking the average uncertainty of the y value, r . All values recorded on *Table-7* (rushed, will be refined).

Table-7: Derived instantaneous initial rate r_0 of different catalysts reacting with the prepared H_2O_2 solution, with the relevant properties of each catalyst attached.

Catalysts	Derived instantaneous initial rate r_0 ($\text{cm}^3 \text{ s}^{-1}$), with average error
Manganese (IV) Oxide	0.41 ± 0.09
Lead (II, IV) Oxide	2.6 ± 0.7
Potassium Iodide (undisturbed)	0.31 ± 0.08
Copper (II) Oxide	0.003 ± 0.001
Iron (III) Oxide	No data (≈ 0)
Potassium Iodide (swirled)	1.0 ± 0.3



Conclusion (will further develop and organize, please suggest how this could be done)

The results of this experiment strongly disagrees with my hypothesis that potassium iodide will be the most effective catalyst for the decomposition of hydrogen peroxide per unit mass. The experiment strongly suggests that lead (II, IV) oxide is the most effective catalyst per unit mass out of all five, where it has the highest derived instantaneous initial rate of $2.6 \pm 0.7 \text{ cm}^3 \text{ s}^{-1}$. The hypothesized potassium iodide had the second highest initial instantaneous rate when swirled, but had the second lowest initial instantaneous rate when left undisturbed. The margin of error between $1.0 \pm 0.3 \text{ cm}^3 \text{ s}^{-1}$ for swirled potassium iodide does not overlap with the margin of error for lead (II, IV) oxide, which means that the results of this experiment definitively shows that lead (II, IV) oxide is the most effective catalyst out of the five chosen catalyst.

Given the fact that manganese (IV) oxide also had a faster initial instantaneous rate shows that there might be a hidden factor in deciding the efficiency of a catalyst for hydrogen peroxide decomposition. This hidden factor could possible be the adoption effect of transition metal compounds, which should play a significant role in determining the probability of reactants reacting through the catalyzed pathway.

The most plausible explanation for why lead (II, IV) oxide is the most effective catalyst is that it decomposes the most quantity of hydrogen peroxide per catalytic cycle per mol. Another reason why lead (II, IV) is the most effective catalyst is due to how both oxidation states of lead exists in the compound, which allows reduction and oxidation to happen simultaneously in its catalytic cycle, significantly reducing its pathways' net activation energy.

Evaluation (Will expand into paragraph form)

Limitations of method

Issue	Impact	Resolution
The spontaneous decomposition of hydrogen peroxide was not addressed.	Measurements later into the experiment may be conducted on a significantly lower concentration of hydrogen peroxide.	Use fresh hydrogen peroxide each time.
Surface area of the catalysts is quantitatively not controlled	Surface area was forced to be deemed as a property of the catalyst instead of a controlled variable.	(For metal oxides) use metal oxide chips that can be cut into regular shapes to control surface area,
Class B equipments (eg. Pipette, volumetric flask) used in the experiment are relatively inaccurate	Loss of accuracy	Use Class A equipment
Only two repeated trials are conducted per measurement	Loss of reliability	Conduct three or more trials of measurement
Instrument error was too great for the gas syringe	Loss of accuracy	Use a more accurate gas syringe next time.

Scope for further investigation

- Catalytic efficiency per unit mol
- Catalytic efficiency at different concentrations of hydrogen peroxide
- Catalytic efficiency at at different temperature

Works cited

Image:

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H₂O₂ halflife

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