Topic 21 – Speed of Reaction

Subject content

(a) describe the effect of concentration, pressure, particle size and temperature on the speeds of reactions and explain these effects in terms of collisions between reacting particles
(b) define the term catalyst and describe the effect of catalysts (including enzymes) on the speeds of reactions
(c) explain how pathways with lower activation energies account for the increase in speeds of reactions (see also 5(b))
(d) state that some compounds act as catalysts in a range of industrial processes and that enzymes are biological catalysts (see also 5(b), 6.1(c), 8.3(b) and 10(d))
(e) suggest a suitable method for investigating the effect of a given variable on the speed of a reaction
(f) interpret data obtained from experiments concerned with speed of reaction.

Definition

Term	Definition	SI unit
Speed (**rate**) **of reaction**	measurement of how fast or slow a reaction takes place (measured change in quantity of product formed or reactant used per unit time)	
Catalyst	Substance which <u>increases</u> rate of reaction with itself remaining <u>chemically unchanged</u> at the end of reaction	

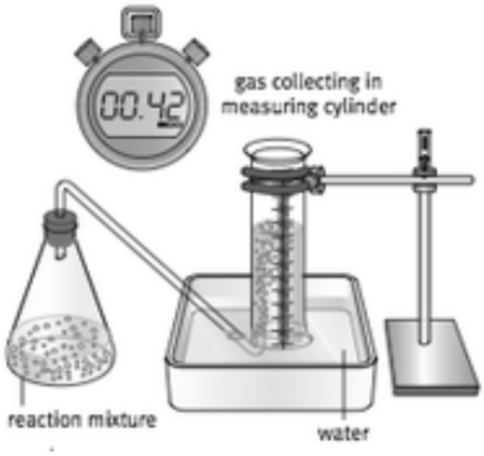
21.1 Measuring Speed of Reaction

Measure speed of reaction → **measurable physical quantities**

1. Change in volume of gas evolved (at fixed time intervals)
2. Change in mass of reactants during reaction (at fixed time intervals)
3. Time taken for reaction to complete
4. Time taken for formation of precipitate

METHOD 1: Change in volume of gaseous reactant / product

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



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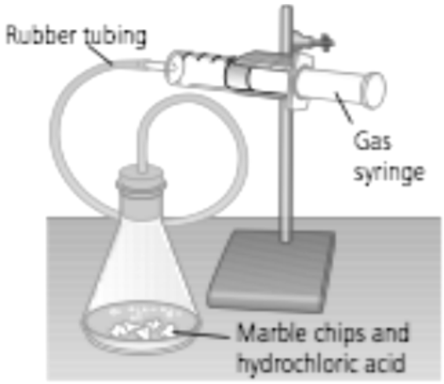
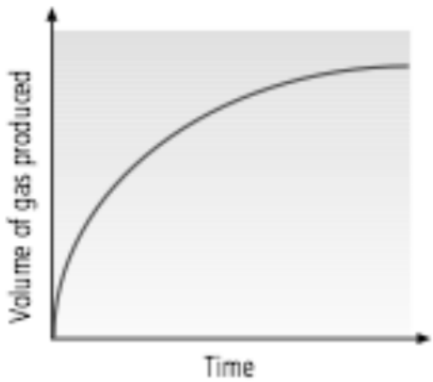
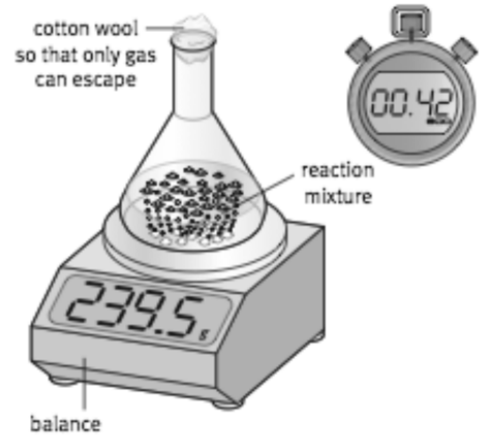


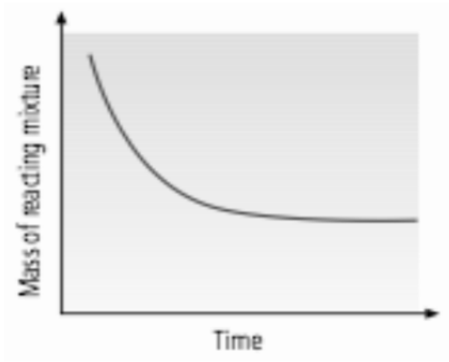


- Reaction produces carbon dioxide (gas), which is collected
- Over time, volume of gas collected increases until it reaches a constant value → reaction has ended

METHOD 2: Change in mass (of conical flask + contents) over time

$\underline{CaCO_3 + 2\ HCl} \rightarrow \underline{CaCl_2 + H_2O} + CO_2$



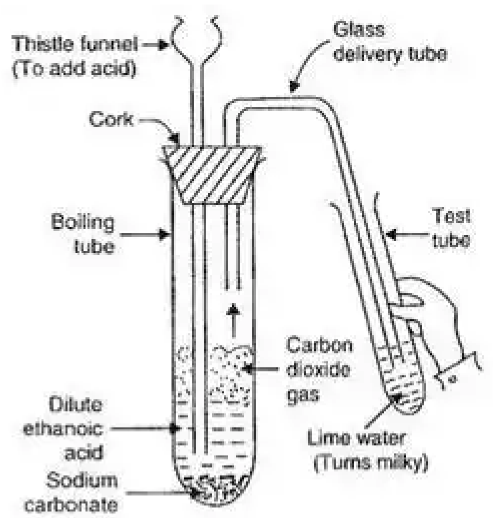


- Reaction produces carbon dioxide (gas), which diffuses out & escapes from conical flask
- Over time, mass of conical flask + contents decreases until it reaches a constant value → reaction has ended

Note:
- Plug mouth of flask with cotton plug → prevent acid spray (absorb HC*l*, prevent HCl from coming out → prevent loss in mass due to loss of acid as result of acid spray - mass lost only due to CO_2 escaping)

METHOD 3: Time taken for reaction to complete (effervescence)

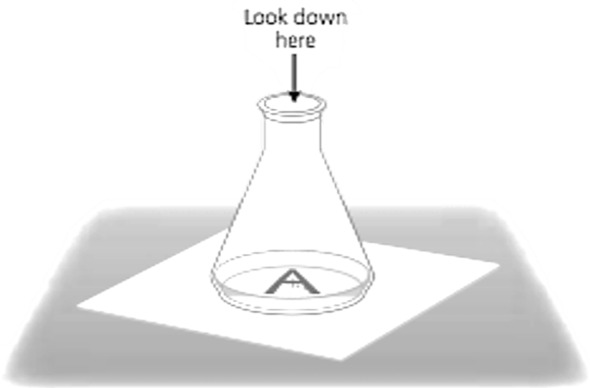
$CaCO_3 + 2\ HCl \rightarrow CaCl_2 + H_2O + \underline{CO_2}$

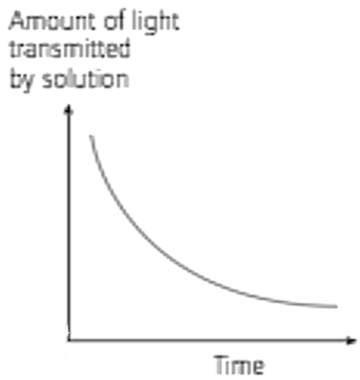


- Reaction produces carbon dioxide (gas), which escapes from reaction mixture

METHOD 4: Time taken for formation of precipitate

$Na_2S_2O_3\ (aq) + 2\ HCl\ (aq) \rightarrow 2\ NaCl\ (aq) + S\ (s) + SO_2\ (g) + H_2O\ (l)$





- Reaction produces yellow precipitate of sulfur
- Over time, enough precipitate is formed to block cross from view

Note:
- Hazardous → sulfur dioxide released as reaction product (particularly risky when investigating effect of temperature on rate as sulfur dioxide is driven out of solution at increased temperatures)
- Use ‘stop bath’ of sodium hydrogencarbonate solution mixed with indicator
  - pour reaction mixture into stop bath as soon as mixture shows desired cloudiness
  - acid and sulfur dioxide are neutralised instantly & indicator shows when stop bath is no longer effective

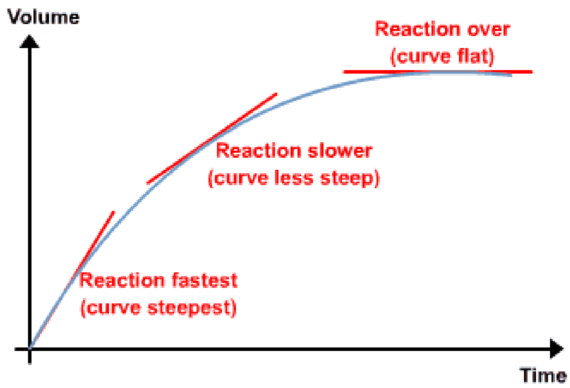
Graph for rate of reaction

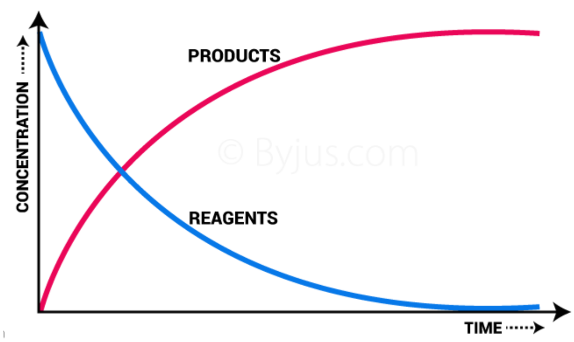
Gradient of tangent at given time on curve

= rate of reaction = $\frac{change\ in\ mass}{change\ in\ time}$

Speed of reaction = $\frac{quantity\ of\ product\ formed\ /\ product\ used}{time\ taken}$

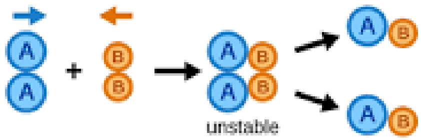
Period	Gradient	Rate of reaction
Beginning	**steep**	high
Middle	**gentle**	low
End	**zero**	stop





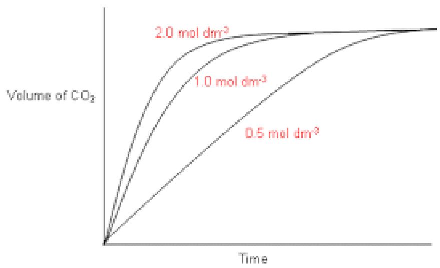
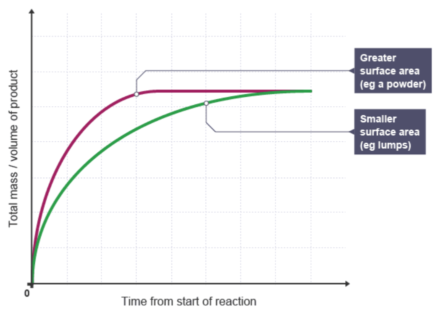
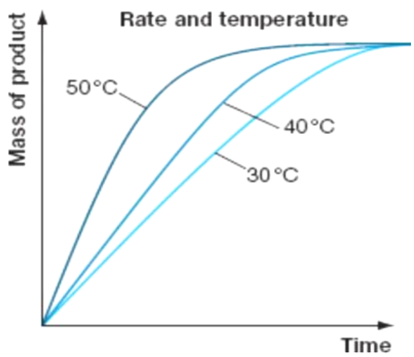
21.2 Factors Affecting the Rate of Reaction

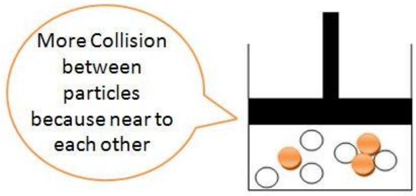
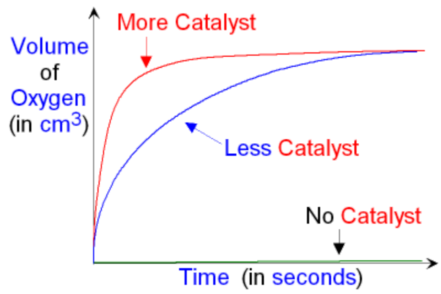
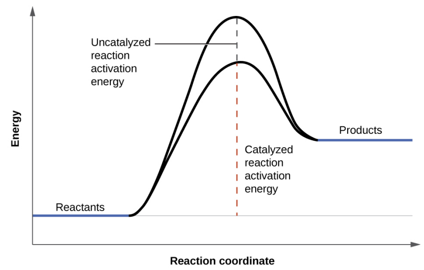
Collision theory

Effective collision	Ineffective collision
	

Factors

1. **Concentration** of reactant solution
2. **Surface area** of solid reactant
3. **Temperature**
4. **Pressure** of reactant gas
5. **Catalyst**

Factor	Explanation	Graph
1. **Concentration**	1) More reacting particles per unit volume → **higher frequency of effective collisions b/w reacting particles**	
2. **Surface area**	1) Greater area of contact b/w reacting particles → **higher frequency of effective collisions b/w reacting particles**	
3. **Temperature**	1) Reacting particles gain more energy → move faster → collide more frequently 2) More reacting particles have energy ≥ activation energy of reaction → **higher frequency of effective collisions b/w reacting particles**	

4. **Pressure**	1) Smaller volume occupied by gas particles – higher no. of reacting particles per unit volume Reacting particles closer to each other → **higher frequency of effective collisions b/w reacting particles**	
5. **Catalyst**	1) Catalyst: provide <u>alternative pathway</u> of <u>lower activation energy</u> for reaction to proceed 2) More reacting particles have energy ≥ activation energy of reaction → **higher frequency of effective collisions b/w reacting particles**	 

<u>**Catalyst**</u>

Examples:

Catalyst	Use
1. **Platinum**	Manufacturing of acid
2. **Iron**	Haber process (nitrogen + hydrogen → ammonia)
3. **Nickel**	Hydrogenation of unsaturated fats → margarine
4. **Vanadium(V) oxide**	Contact process for production of sulfuric acid
5. **Enzymes in yeast**	Sugar → alcohol
6. **Enzymes in bacteria**	Milk → yoghurt

Enzyme: <u>biological</u> catalysts made of <u>protein</u> molecules

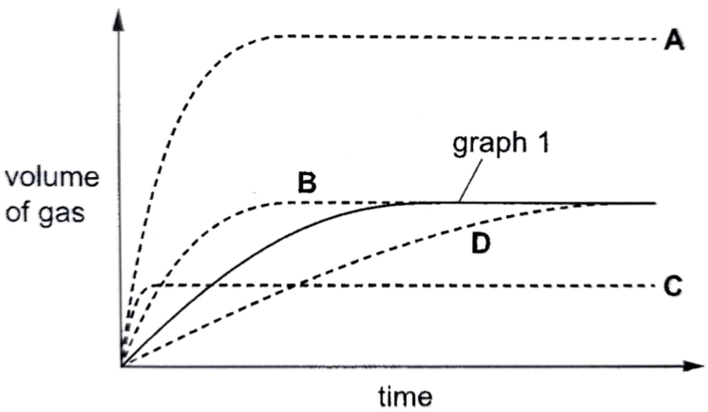
Typical questions

Multiple choice questions

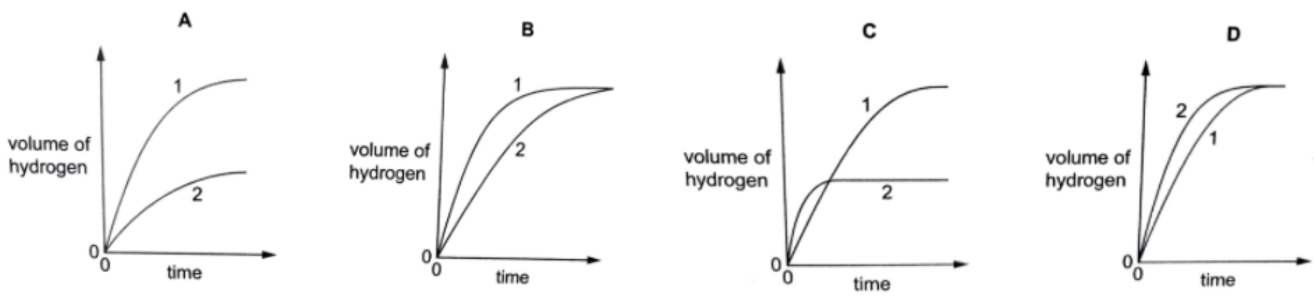
1 Iron reacts with dilute hydrochloric acid at a constant temperature of 25°C.
Which statement about the rate of this reaction is correct? (2021 P1 Q15)

A It decreases as the reaction proceeds.
B It decreases then increases as the reaction proceeds.
C It increases as the reaction proceeds.
D It remains the same as the reaction proceeds.

2 A sample of 0.5 g of magnesium ribbon is reacted with an excess of 1 mol/dm^3 hydrochloric acid. The volume of hydrogen produced over time is measured. The results are plotted to give the graph below.
Which graph would be produced when 0.5 g of magnesium ribbon is reacted with an excess of 2 mol/dm^3 hydrochloric acid under the same conditions? (2020 P1 Q17)



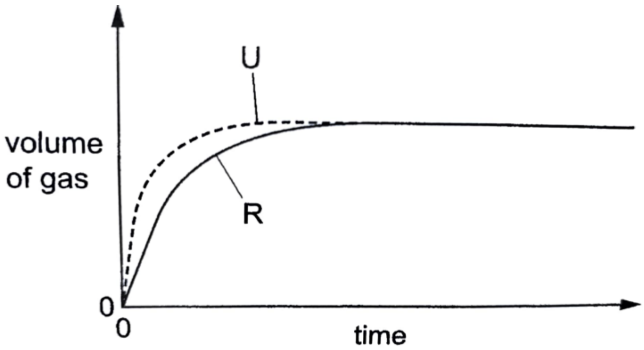
3 Dilute hydrochloric acid is reacted with 1.2 g of magnesium ribbon at room temperature in two experiments, experiment 1 and experiment 2.
In experiment 1, 100 cm^3 of 1 mol/dm^3 hydrochloric acid is used.
In experiment 2, 50 cm^3 of 2 mol/dm^3 hydrochloric acid is used.
The volume of hydrogen given off is plotted against time.
Which graph is correct? (2019 P1 Q17)



4 How is the activation energy for a reaction between two gases changed when it is carried out either in the presence of a catalyst or when the temperature is increased? (2019 P1 Q18)

	change in activation energy	
	addition of catalyst	increase in temperature
A	decreases	decreases
B	decreases	stays the same
C	increases	decreases
D	increases	stays the same

5 1 mol of X reacts with 1 mol of Y to produce a gas.
A student investigates the rate of this reaction by measuring the volume of gas produced at timed intervals.
He plots his results on a graph.
The table below gives the volumes and concentrations of X and Y that he uses to produce line R.



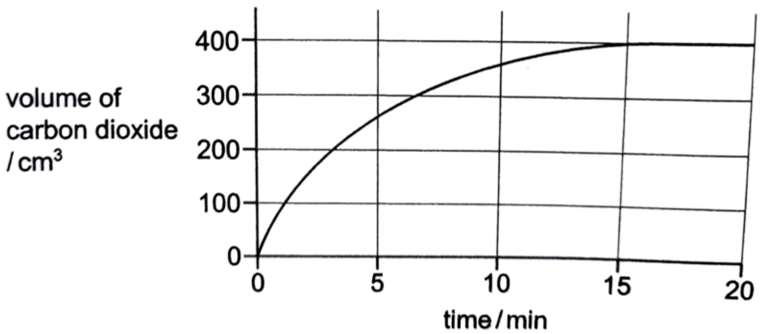
	X	**Y**
volume / cm^3	100	100
concentration / mol/dm^3	1.0	1.0

The students varies both volume and concentration of X and Y over a series of experiments. The results of one of these experiments is plotted on the same graph.
Which row shows the volumes and concentrations that the students used to obtain line U?

(2018 P1 Q19)

	X		Y	
	volume / cm^3	concentration / mol/dm^3	volume / cm^3	concentration / mol/dm^3
A	25	2.0	100	1.0
B	100	1.0	50	2.0
C	100	1.0	200	0.5
D	400	0.5	400	0.5

6 A student added excess hydrochloric acid to calcium carbonate. As the reaction proceeded, he measured the volume of carbon dioxide released, at room temperature and pressure, and plotted a graph. (2017 P1 Q16)



$CaCO_3$ (s) + 2 HCl (aq) → $CaCl_2$ (aq) + CO_2 (g) + H_2O (*l*)

What can the student conclude from the information?

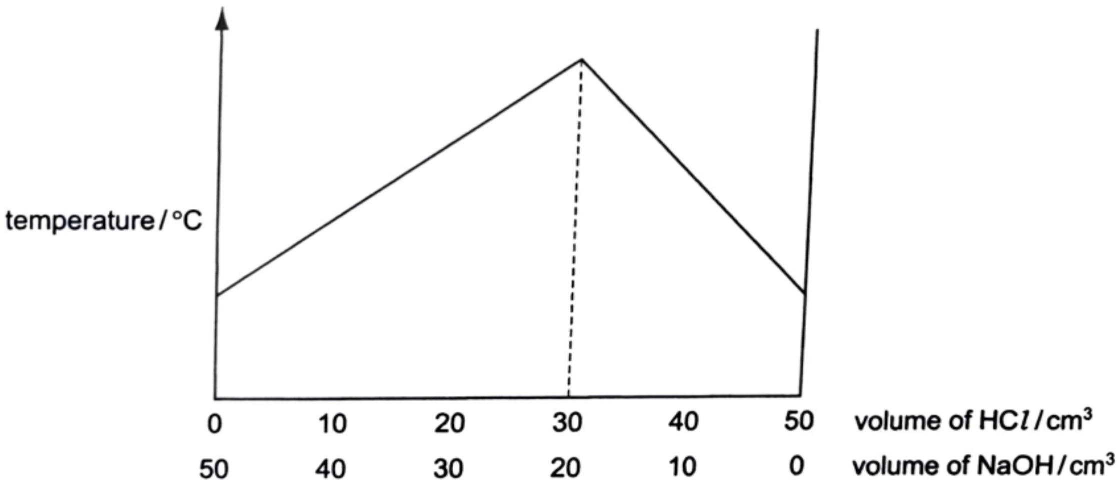
1. The number of moles of calcium carbonate used was 1.67×10^{-2}
2. During the reaction, the rate steadily increased.
3. After 15 minutes, the reaction has stopped.

A 1, 2 and 3
B 1 and 2 only
C 1 and 3 only
D 3 only

7 An aqueous solution of hydrochloric acid has a concentration of 2.0 mol/dm^3.
Different volumes of the acid are added to different volumes of aqueous sodium hydroxide.

$NaOH + HCl \rightarrow NaCl + H_2O$

The maximum temperature of each mixture is measured. The graph shows the results.



What is the concentration of the aqueous sodium hydroxide? (2013 P1 Q17)

A 0.67 mol/dm^3
B 1.3 mol/dm^3
C 1.5 mol/dm^3
D 3.0 mol/dm^3

8 When excess magnesium ribbon is added to dilute hydrochloric acid, the reaction gradually becomes slower and finally stops. Which of the following statements best explains this observation?

A The concentration of the hydrochloric acid decreases until it finally becomes zero.
B The magnesium ribbon is slowly being coated with an insoluble layer of magnesium chloride.
C The magnesium ribbon gradually becomes smaller.
D The temperature of the reaction mixture gradually decreases as the reaction proceeds.

9 Excess hydrochloric acid is added to a given mass of calcium carbonate. A graph of volume of carbon dioxide produced against time is plotted.

Which of the following statements about this experiment is true?

A At 2.4 minutes, all the calcium carbonate has reacted.
B The reaction is complete after 3.0 minutes.
C The speed of the reaction is fastest at 3.0 minutes.
D The time taken for half the mass of calcium carbonate to react is 1.1 minutes.

10 Which of the following acids reacts the fastest when 1.0 g of magnesium powder is added to it? (Assume that all the experiments are carried out at the same temperature.)

A 50.0 cm^3 of 1.0 mol/dm^3 sulfuric acid
B 50.0 cm^3 of 1.0 mol/dm^3 hydrochloric acid
C 50.0 cm^3 of 1.0 mol/dm^3 nitric acid
D 100.0 cm^3 of 1.0 mol/dm^3 ethanoic acid

Structured questions

1 The 'iodine clock' reaction is an experiment that is used to investigate rates of reaction.
Aqueous iodide ions are mixed with other reactants and a series of reactions takes place to produce iodine.
The solution turns blue-black when a fixed amount of iodine has been produced.
The conditions of the reaction are changed by changing the concentration of iodide ions or temperature or by adding a catalyst.
These changes affect the time taken for the solution to turn blue-black.

The table below shows the conditions and results for a series of experiments.

experiment	concentration of iodide ions / mol/dm^3	temperature / °C	catalyst added to reaction mixture	time taken for blue-black colour to appear / s
1	0.1	20	none	50
2	0.2	20	none	27
3	0.2	40	none	15
4	0.2	20	Cu^{2+} ions	20

(2021 P2 B8 OR)

(a) One of the experiments is used as a reference to compare the effect of the variables.
Which experiment is used as a reference?
Explain how you made your choice. [2]

Experiment 2.

- Compared to experiment 1, concentration of iodide ions used is the **only condition changed**.
- Compared to experiment 3, temperature is the **only condition changed**.
- Compared to experiment 4, presence of catalyst is the **only condition changed.**

(b) Use ideas about collisions between particles to explain why changing the conditions shown in the table above changes the time taken for the blue-black colour to appear. [5]

Factor	Explanation	Effect
Concentration Concentration of iodide ions is decreased from 0.2 mol/dm^3 to 0.1 mol/dm^3	• Fewer reactant particles per unit volume • Lower frequency of effective collisions decreases • Speed of reaction is lower	Time taken for blue-black colour to appear increases from 27 s to 50 s
Temperature Temperature is	• Reactant particles gain energy and more particles possess energy	Time taken for blue-black colour to

increased from 20°C to 40°C	equal to or greater than activation energy ● Higher frequency of effective collisions ● Speed of reaction is higher	appear decreases from 27 s to 15 s
Catalyst Cu^{2+} ions are added as a catalyst	● Provide alternative pathway for reaction to proceed, which involves lower activation energy ● More colliding particles possess energy equal to or greater than activation energy ● Higher frequency of effective collisions ● Speed of reaction is higher	Time taken for blue-black colour to appear decreases from 27 s to 20 s

(c) The equation shows the reaction that produces iodine.

$$2\ I^- (aq) + H_2O_2 (aq) + 2\ H^+ (aq) \rightarrow I_2 (aq) + 2\ H_2O (l)$$

In every experiment, the volume of aqueous iodide ions used is 10 cm^3 and acid is added in excess. 30 cm^3 of 0.05 mol/dm^3 aqueous hydrogen peroxide is used.
Which is the limiting reactant at the start of each experiment? Show your work. [3]

No. of moles of H_2O_2 = 0.05 mol/dm^3 x 0.030 dm^3 = 0.0015 mol

In experiment 1,
No. of moles of I^- = 0.1 mol/dm^3 x 0.010 dm^3 = 0.001 mol

In experiment 2, 3, 4,
No. of moles of I^- = 0.2 mol/dm^3 x 0.010 dm^3 = 0.002 mol

From the equation, 1 mol of H_2O_2 would need to react with 2 mol of I^-.
0.0015 mol of H_2O_2 would need to react with 0.003 mol of I^-.
For all 4 experiments, no. of moles of I^- used is less than 0.003 mol.
Therefore, $\mathbf{I^-}$ is the limiting reactant.

2 A student investigated the rate of reaction when dilute acid reacts with excess solid copper(II) carbonate.
He used the same volume of acid each time. He measured the time taken to collect 10 cm^3 of gas at room temperature and pressure. He also measured the total volume of gas at the end of the experiment at room temperature and pressure.
The table below shows his results.

experiment	acid	concentration / mol/dm^3	time taken to collect 10 cm^3 of gas / s	total volume of gas / cm^3
1	hydrochloric	0.5	15	150
2	hydrochloric	1.0	6	300
3	hydrochloric	0.5	7	150
4	nitric	0.5	15	150

(2017 P1 B9 EITHER)

(a) Give the formula for the salt formed in experiment 4. [1]

$Cu(NO_3)_2$

(b) The student carried out three experiments using acid at room temperature and one experiment using acid at a higher temperature.
Which experiment was carried out at a higher temperature? Explain your reasoning. [2]

Experiment 3.

Comparing experiments 1, 3 and 4 which used acid of the same concentration, the time taken to collect 10 cm^3 of gas in experiment 3 was about half that of the other two temperatures.

(c) Explain, in terms of collisions between reacting particles, why a higher temperature affects the rate of reaction. [3]

- When the temperature is increased, the reactant particles have more kinetic energy, move faster and collide with each other more frequently.
- At higher temperatures, more particles possess energy equal to or greater than the activation energy, resulting in a higher frequency of effective collisions.
- Thus the rate of reaction is higher.

(d) The student carried out two further experiments at room temperature using 0.5 mol/dm3 ethanoic acid and 0.5 mol/dm3 sulfuric acid.
He used the same volume of acids as in the previous experiments with excess solid copper(II) carbonate.
Complete the table to predict the results he should expect and explain how you arrived at your answers. [4]

experiment	acid	concentration / mol/dm^3	time taken to collect 10 cm^3 of gas / s	total volume of gas / cm^3
5	ethanoic	0.5	1500	150
6	sulfuric	0.5	7.5	300

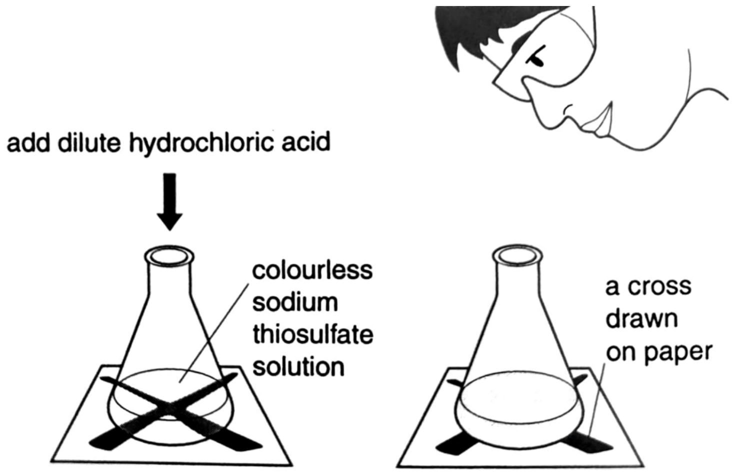
Ethanoic acid:

- Ethanoic acid is a weak monobasic acid and will only ionise partially in water (about 1%) to give a lower concentration of H^+ ions.
- This results in lower rate of reaction by 100 times (thus 1500 s) as compared to hydrochloric acid in experiment 1.
- The same volume of gas is produced because both ethanoic acid and hydrochloric acid are monobasic and contain the same amount (same number of moles) of acid reactant which is the limiting reactant.

Sulfuric acid:

- Sulfuric acid is a dibasic strong acid and ionises completely in water to produce twice the concentration of H^+ ions as compared to hydrochloric acid of the same concentration and volume.
- The rate of reaction will be doubled (thus 7.5 s).
- The total volume of gas produced will also be doubled (thus 300 cm^3).

3 The rate of the reaction between dilute hydrochloric acid and sodium thiosulfate solution can be investigated using a cross drawn on a piece of paper.



As the reaction progresses, it becomes more difficult to see the cross through the solution.

(2013 P2 A3)

(a) Look at the equation for the reaction.

$$Na_2S_2O_3\ (aq) + 2\ HCl\ (aq) \rightarrow 2\ NaCl\ (aq) + S\ (s) + SO_2\ (g) + H_2O\ (l)$$

Explain why it becomes more difficult to see the cross as the reaction progresses. [2]

As the reaction progresses, precipitate of sulfur formed increases.
As the reaction mixture becomes cloudy, visibility of the cross decreases.

(b) The table shows the results of some experiments to investigate the rate of reaction, using different concentrations of sodium thiosulfate.
A student measured the time from when the acid was added until the cross can no longer be seen.
The same concentration and volume of dilute hydrochloric acid and the same volume of sodium thiosulfate were used each time.

concentration of $Na_2S_2O_3$ / mol/dm^3	**time until cross cannot be seen / s**
1.0	8
0.8	10
0.4	20
0.2	39

(i) Using ideas about collisions between particles, explain the trend in the results. [3]

- The higher the concentration of $Na_2S_2O_3$, the greater the number of $S_2O_3^{2-}$ ions per unit volume.
- Hence, more collisions between $S_2O_3^{2-}$ and H^+ ions, resulting in higher frequency of effective collisions.
- Reaction speed (production of sulfur solids) is faster, so time taken for cross to disappear becomes shorter.

(ii) The experiment was repeated with another concentration of sodium thiosulfate. The cross could not be seen after 14 s.
Estimate the concentration of sodium thiosulfate that was used. [1]

0.6 mol/dm^3

(c) Some metal oxides can act as catalysts for the reaction.

(i) A student thinks that chromium(III) oxide acts as a catalyst for the reaction. Describe what he should do and the results he would obtain if he is right. [3]

- The experiment is repeated with the same volume and concentration of dilute hydrochloric acid and the same volume of sodium thiosulfate with concentration of 0.2 mol/dm^3 and 0.5 g of chromium(III) oxide added.
- If chromium(III) oxide is the catalyst, the time until the cross cannot be seen would be much shorter than 39 g.

(ii) Catalysts lower the activation energy for the reaction. Explain how they do this. [1]

Catalysts provide alternative pathways of reaction with lower activation energies.

4 When liquid hydrogen peroxide (H_2O_2) is mixed with liquid hydrazine (N_2H_4), a very fast exothermic reaction takes place which can propel a rocket. The products of the reaction are nitrogen and steam.

(a) Suggest a reason why this fast reaction is necessary.

To provide sufficient energy for the propulsion of the rocket.

(b) Write a balanced reaction equation (including state symbols) for this reaction involving hydrogen peroxide and hydrazine.

$2\ H_2O_2\ (l) + N_2H_4\ (l) \rightarrow N_2\ (g) + 4\ H_2O\ (g)$

(c) If the rocket is loaded with 680 kg of hydrogen peroxide, calculate the mass of hydrazine which will be needed to react with it.

No. of moles of H_2O_2 = $\dfrac{680 \times 10^3\ g}{[2(1) + 2(16)]\ g/mol}$ = 2×10^4 mol

No. of moles of N_2H_4 required = $\dfrac{1}{2} \times (2 \times 10^4 \text{ mol}) = 1 \times 10^4$ mol

Mass of N_2H_4 = (1×10^4 mol) × [2(14) + 4(1)] g/mol = **320 kg**

5 Equal amounts of magnesium strip are added to hydrochloric acid (HCl) and sulfuric acid (H_2SO_4) of same molarity and volume. Which reaction is expected to be faster?

(a) Explain your answer.

Sulfuric acid (H_2SO_4).
The acids dissociate in water as follows:
$H_2SO_4 \rightarrow 2\ H^+ + SO_4^{2-}$
$HCl \rightarrow H^+ + Cl^-$
For the same molarity and volume of acid, there are more H^+ ions in sulfuric acid than in hydrochloric acid. Hence, the reaction is faster in sulfuric acid.

(b) List three ways to further increase the speed of these reactions.

1. Increase the temperature of the reactions
2. Use finely divided magnesium powder
3. Increase the concentration of the acids