Section A

Question	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Answer	B	C	C	D	A	B	B	D	B	C	A	C	D	C	A

MCQ worked solutions

A1 (B) After cooling back to room temperature and pressure, H_2O condenses back to liquid state.

$$4CH_3NH_2(g) + 9O_2(g) \longrightarrow 4CO_2(g) + 2N_2(g) + 10H_2O(l)$$

Initial V/ cm^3	20	60	0	0	0
Change in V/cm^3	−20	−45	+20	+10	−
Final V/ cm^3	0	15	20	10	−

Final total volume = 15 + 20 + 10 = 45 cm^3

A2 (C) Mol ratio of MnO_4^{2-} to MnO_4^- = 3 : 2
2 mol of MnO_4^{2-} is oxidised to 2 mol of MnO_4^-.

Since 3 mol of MnO_4^{2-} underwent disproportionation, 3−2 = 1 mol of MnO_4^{2-} is reduced to the manganese-containing product.

Oxidation no. increased from +6 to +7 from MnO_4^{2-} to MnO_4^-.

Hence, amt of e^- lost by 2 mol of MnO_4^{2-} = 2 mol

Total amt of e^- lost = total amt of e^- gained,
Amt of e^- gained by 1 mol of MnO_4^{2-} = 2 mol
Hence, the oxidation number of Mn decreases by 2 to form the manganese-containing product.

Oxidation number of the product = +6 − 2 = +4
The only manganese-containing product in the options with a oxidation number of +4 is MnO_2.

A3 (C) The data for gold should be ignored as the question is about the A_r value for copper.

A_r = (63×0.62 + 65×0.32) ÷ 0.94 = 63.7

A4 (D) Option 1 is incorrect as ^{36}S has a nucleon number of 36 while ^{37}Cl has a nucleon number of 37. The charge of the ion indicates the number of electrons lost or accepted and does not affect the nucleon number.

Option 2 is correct as the S atom accepts 2 electrons to form an ion with an outer electronic configuration of $3s^2\ 3p^6$, while the Cl atom accepts 1 electron to form an ion with an outer electronic configuration of $3s^2\ 3p^6$

Option 3 is incorrect. $^{36}S^{2-}$ has 16+2 = 18 electrons and 36−16= 20 neutrons. $^{37}Cl^-$ has 17+1 = 18 electrons and 37−17= 20 neutrons.

A5 (A) As Ba is in group 2, it loses 2 valence electrons to form Ba^{2+}. Hence, the anion has a charge of 2−.

In the O_2^{2-} anion, each of the 2 electrons from Ba is accepted by each of the 2 oxygen atoms.

A6 (B) Recall that a gas deviates from ideal gas behavior at <u>high pressure</u> and <u>low temperature</u>. The higher the pressure and the lower the temperature, the greater the deviation from ideality.

A7 **(B)** Assuming ideal gas behaviour,

$pV = nRT$

$n = \frac{pV}{RT}$

Since pressure is kept constant at 1 atm,

$\frac{\text{no. of moles of air in the heated balloon}}{\text{initial no. of moles of air in the balloon}} =$

$\frac{101325 \times 5500}{R \times (65 + 273)} \times \frac{R \times (25 + 273)}{101325 \times 5000} = 0.97$

Note: Since p and R are constants, students can also make use of $n \propto \frac{V}{T}$ and thus $\frac{n_2}{n_1} = \frac{V_2}{T_2} \times \frac{T_1}{V_1}$.

A8 **(D)** $COCl_2(g) \rightleftharpoons CO(g) + Cl_2(g)$

$K_c = a = \frac{[CO][Cl_2]}{[COCl_2]}$

Let K_c' be the equilibrium constant of the reaction below.

$2CO(g) + 2Cl_2(g) \rightleftharpoons 2COCl_2(g) \qquad K_c'$

$K_c' = \frac{[COCl_2]^2}{[CO]^2[Cl_2]^2} = (\frac{[COCl_2]}{[CO][Cl_2]})^2 = (\frac{[CO][Cl_2]}{[COCl_2]})^{-2}$

$= (a)^{-2} = \frac{1}{a^2}$

A9 **(B)** Statement 1 is correct. As the equilibrium system is homogeneous (all species are in the same phase), H_2O is not a solvent, $[H_2O]$ is not constant and should appear in the equilibrium constant expression.

Statement 2 is incorrect. Equilibrium constant, K_c (or K_p), is only affected by temperature changes. Increasing amount of CH_3OH, and hence $[CH_3OH]$ will not have any effect on equilibrium constant.

Statement 3 is correct. Adding $HCO_2C_2H_5$ to the equilibrium mixture will shift the equilibrium position of ② to the left, leading to an increase in $[HCO_2H]$. The increase in $[HCO_2H]$ in turn result in the equilibrium position of ① to shift to the right, leading to an increase in concentration and hence amount of HCO_2CH_3.

① $HCO_2H(l) + CH_3OH(l) \rightleftharpoons HCO_2CH_3(l) + H_2O(l)$ K_1

② $HCO_2H(l) + C_2H_5OH(l) \rightleftharpoons HCO_2C_2H_5(l) + H_2O(l)$ K_2

A10 **(C)** $\Delta H_r^\ominus = \Delta H_f^\ominus[PCl_5(l)] - [\Delta H_f^\ominus[PCl_3(l)] + \Delta H_f^\ominus[Cl_2(g)]]$

Since $\Delta H_f^\ominus$ of an element at its standard state = 0, $\Delta H_f^\ominus[Cl_2(g)] = 0$, and the question states that $\Delta H_f^\ominus[PCl_5(l)] < 0$ and $\Delta H_f^\ominus[PCl_3(l)] < 0$,

$\Delta H_f^\ominus[PCl_5(l)] - \Delta H_f^\ominus[PCl_3(l)] = -124$

$\Delta H_r^\ominus$ is less negative than $\Delta H_f^\ominus[PCl_5(l)]$.

A11 **(A)** Reaction 1

$H_2SO_4 + 2NaOH \rightarrow Na_2SO_4 + 2H_2O$

$n(H_2SO_4) = 2.00 \times 10^{-3}$ mol

$n(NaOH) = 3.00 \times 10^{-3}$ mol

NaOH is the limiting reagent.

$n(H_2O) = 3.00 \times 10^{-3}$ mol

$q_1 = 50 \times 4.18 \times \Delta T_1$

$\Delta H_1 = -\frac{50 \times 4.18 \times \Delta T_1}{3.00 \times 10^{-3}}$ J mol^{-1}

Reaction 2

$HCl + NaOH \rightarrow NaCl + H_2O$

$n(HCl) = 2.00 \times 10^{-3}$ mol

HCl is the limiting reagent.

$n(H_2O) = 2.00 \times 10^{-3}$ mol

$q_2 = 50 \times 4.18 \times \Delta T_2$

$\Delta H_2 = -\frac{50 \times 4.18 \times \Delta T_2}{2.00 \times 10^{-3}}$ J mol^{-1}

Since reactions 1 and 2 are neutralisation reactions between strong acids and a strong base, $\Delta H_1 = \Delta H_2$

$-\frac{50 \times 4.18 \times \Delta T_1}{3.00 \times 10^{-3}} = -\frac{50 \times 4.18 \times \Delta T_2}{2.00 \times 10^{-3}}$

$\frac{\Delta T_1}{\Delta T_2} = \frac{3}{2} = 1.5$

From Pg 11 of Chemical Energetics 1 lecture notes: The neutralisation reaction between a weak acid – strong base is less exothermic than that of the strong acid –strong base neutralisation reaction. This is because during the neutralisation reaction, the CH_3COOH molecules undergo further dissociation to produce H^+ ions for reaction with the OH^- ions. Some energy is consumed to bring about further dissociation of the CH_3COOH molecules during the neutralisation reaction. So, the energy released from the reaction will be less. In this case, $\Delta H_{neut}^\ominus$ between CH_3COOH and NaOH is less negative than that between HCl (or H_2SO_4) and NaOH. Hence, options B and D are incorrect.

A12 (C)

$$200 \xrightarrow{1^{st}\ t_{1/2}} 100 \xrightarrow{2^{nd}\ t_{1/2}} 50 \xrightarrow{3^{rd}\ t_{1/2}} 25$$

$24\ h = 3 \times t_{1/2} \Rightarrow t_{1/2} = 8\ h$

A13 (D)

Option 1 is incorrect.
The shapes of the two graphs reflect how $[H_2O_2]$ changes with time for an autocatalytic reaction. However, the catalytic decomposition of H_2O_2 is not an autocatalytic reaction.

Option 2 is incorrect.
The amount of product obtained is independent of the amount of catalyst used. Using double the mass and hence amount of catalyst does not give a higher yield of product.

Option 3 is correct.
Refer to Pg 40 of Reaction Kinetics lecture notes. At low $[H_2O_2]$, the reaction is first order with respect to H_2O_2 as not all the active sites of the catalyst are occupied. At high $[H_2O_2]$, the reaction is zero order with respect to H_2O_2 as all the active sites of the catalyst are saturated with H_2O_2. The rate of reaction increases with the amount of catalyst used.

A14 (C)

Option A is incorrect as a meso compound has a plane symmetry, cannot rotate plane-polarised light and thus is not optically active.

Option B is incorrect as enantiomers interact differently with chiral molecules.

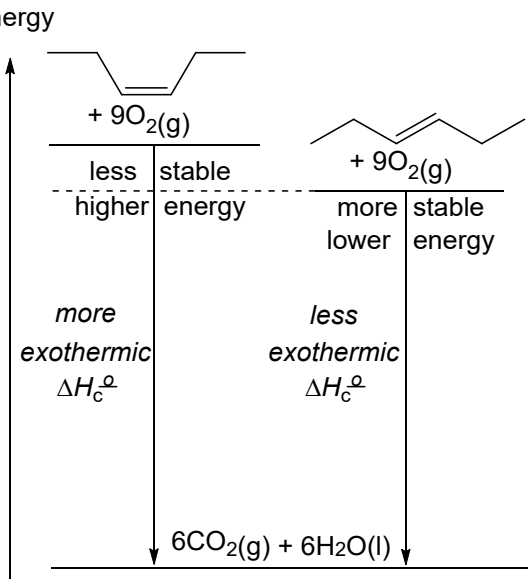
Option C is correct as a racemic mixture is made of equal proportion of two enantiomers and enantiomers do not have a plane of symmetry.

Option D is incorrect as a molecule with only one chiral centre must be chiral, and cannot be a meso compound, and hence will be able to rotate plane-polarised light.

A15 (A)

Cis-hex-3-ene has a higher boiling point than *trans*-hex-3-ene as *cis*-hex-3-ene is slightly polar while *trans*-hex-3-ene is non-polar.

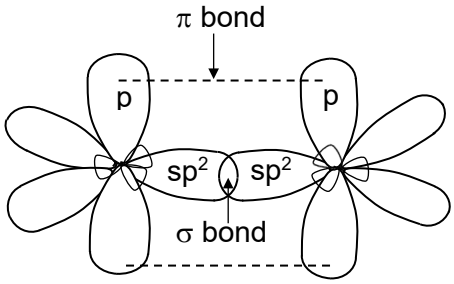
Cis-hex-3-ene has a more negative $\Delta H_c^{\ominus}$ *trans*-hex-3-ene as *cis*-hex-3-ene is less stable due to steric strain arising from crowding between two alkyl groups on the same side of the C=C.



Section B

B1(a) Hybridisation of carbon atom in ethene: $\underline{sp^2}$

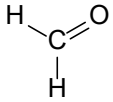
The two atoms form a $\underline{\sigma\text{–bond via the head–on overlapping}}$ of two sp^2 hybrid orbitals.
They also form a $\underline{\pi\text{–bond via the side–on overlapping}}$ of the two unhybridised p orbitals.



Comments:
- The question required the drawing of "**a** diagram (i.e. one diagram) to show how orbitals **overlap** to form the C**=**C bond".
- A number of students did not mention about head-on or side-on overlap, or did not name the σ and π bonds.
- Some students (incorrectly) thought that the π bond is formed between 2 other sp^2 hybrid orbitals.
- The diagram needs to be clearly shown that the 3 sp^2 hybrid orbitals is trigonal planar and the π bond is perpendicular to the σ bond i.e. 90^o to each other.

B1(b) CH_3CH_3 and CH_2O have simple molecular structure. The $\underline{\text{permanent dipole-permanent dipole between } CH_2O \text{ molecules}}$ are $\underline{\text{stronger}}$ and require $\underline{\text{more energy}}$ to overcome than the $\underline{\text{instantaneous dipole-induced dipole between } CH_3CH_3 \text{ molecules}}$, hence CH_2O has a higher boiling point than CH_3CH_3.

Comments:
- This question was generally well-attempted.
- There is no hydrogen bonding between CH_2O molecules, as the H atoms are covalently bonded to C rather than O.



- As both CH_3CH_3 and CH_2O have simple molecular structures, the difference in their boiling points is due to the differences in their $\underline{\text{intermolecular forces of attraction}}$, not covalent bonds.

B1(c) CH_3NH_2 has $\underline{\text{3 bond pairs and 1 lone pair}}$ around N. As $\underline{\text{lone pair-bond pair repulsion is greater than bond pair-bond pair repulsion}}$, to minimize repulsion between electron pairs, its molecular shape is $\underline{\text{trigonal pyramidal}}$, bond angle is $\underline{107°}$

Comments:
- Students should $\underline{\text{compare}}$ the $\underline{\text{types of repulsions}}$ between different electron pairs ($\underline{\text{lone pair-bond pair vs bond pair-bond pair}}$) clearly. They should avoid phrasing such as "repulsion exerted by a lone pair is greater than a bond pair" as without mentioning "… on another bond pair", it is not specific, as the repulsion is between 2 pairs of electrons.

B1(d) The first ionisation energies of the elements <u>generally increase</u> across a period.

Across a period, <u>nuclear charge increases</u> and electrons are added to the same outermost shell, but <u>shielding effect remains approximately constant</u>. Hence, <u>electrostatic attraction</u> between the nucleus and the valence electrons <u>increases</u>, resulting in an increase in the energy required to remove the valence electron from an atom.

Irregularity: the first ionisation energy of A*l* is <u>lower</u> than that of Mg.

Mg: $1s^2\ 2s^2\ 2p^6\ 3s^2$ A*l*: $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^1$

The <u>3p</u> electron to be removed from A*l* is at a <u>higher energy level</u> than the <u>3s</u> electron to be removed from Mg. Hence, less energy is required to remove the 3p electron in A*l* than the 3s electron in Mg.

Comments:
- The first half of the question was generally well-attempted.
- The explanation for the irregularity was not well-attempted. Some students were confused regarding the relative energy levels of 3s and 3p, while some students thought that an unpaired electron is easier to remove than a paired electron.
- The question required an explanation for the general trend in 1st IE across Period 3 elements and why aluminium does not follow this trend. Students should read the question carefully and should not be explaining in terms of the relative energy levels of 2s and 2p.

B1(e)(i)

Comments:
- Many students found this question challenging.
- Many students had missing partial charges, lone pair on the O atom or label for the hydrogen bond.
- It is sufficient to show one hydrogen bond in your diagram. Please note that the electron pair geometry is tetrahedral with respect to each oxygen atom and hence the hydrogen bonds should not be "crossing everywhere".
- The lone pair needs to be clearly shown on the hydrogen bond.

B1(e)(ii) Each oxygen atom in ice is <u>tetrahedrally bonded</u> to four hydrogen atoms, two by covalent bonds and two by hydrogen bonds. This enables the H_2O molecules in ice to form rigid, <u>open/spaced out,</u> 3–dimensional networks, leading to the same number of H_2O molecules in ice occupying a larger unit volume.

Comments:
- While students generally recognised that the molecules in ice were more "spaced out", few provided a sufficient explanation related to its structure.

B2(a)(i) $K_p = \dfrac{(P_{SO_2})^2(P_{O_2})}{(P_{SO_3})^2}$ atm

Comments:
- The K_p expression was generally well done, with only a handful of students who incorrectly expressed in terms of concentrations. Note that in Chemistry, the square brackets [ ] is used to denote concentration.
- Some students did not read the question carefully and missed stating the units of K_p.

B2(a)(ii) By conservation of mass,
mass of initial sample of SO_3 = mass of gaseous mixture at equilibrium = 8.01 g

At equilibrium,

$$\text{density of gaseous mixture} = \frac{\text{mass of gaseous mixture}}{\text{volume of gaseous mixture}}$$
$$= \frac{8.01}{\text{volume of gaseous mixture}} = 1.60 \text{ g dm}^{-3}$$

$$\text{Volume of gaseous mixture} = \frac{8.01}{1.60} = 5.01 \text{ dm}^3 \text{ (shown)}$$

Comments:
- This question required understanding the concept of mass conservation in a reaction.
- Some students attempted to solve using the I.C.E table and/or pV=nRT.

B2(a)(iii) At equilibrium,
pV = nRT

$$\text{Total amount of gas} = n = \frac{pV}{RT} = \frac{(1.80 \times 101325)(5.01 \times 10^{-3}))}{(8.31)(600 + 273)} = 0.12595 \text{ mol}$$
$$= 0.126 \text{ mol}$$

Comments:
- This question was generally well done.
- Students should note that the reaction conditions are not under r.t.p and hence the molar volume of gas at r.t.p (i.e. 24 $\text{dm}^3\ \text{mol}^{-1}$) should not be used.
- For the conversions of T/°C to T/K and P/atm to P/Pa, students should follow the values given in the *Data Booklet*: 273 K [0 °C] and 101325 Pa [1 atm].

B2(a)(iv) $$\text{Initial amount of } SO_3 = \frac{8.01}{32.1 + (3 \times 16.0)} = 0.100 \text{ mol}$$

	$2SO_3(g)$	$\rightleftharpoons$	$2SO_2(g)$	+	$O_2(g)$
initial amount / mol	0.100		0		0
change in amount / mol	–2y		+2y		+y
equilibrium amount / mol	0.100 – 2y		2y		y

Total amount of gas at equilibrium = 0.100 – 2y + 2y + y = 0.100 + y = 0.12595 mol
y = 0.02595

Amount of SO_3 decomposed = 2y = 2(0.02595) = 0.0519 mol

$$\text{Percentage decomposition of } SO_3 = \frac{0.0519}{0.100} \times 100\% = 51.9\%$$

Comments:
- Depending on the context of question, students are encouraged to construct the I.C.E table to guide them in solving equilibrium questions. Also, it is important to consider the mole ratio of the reactants and products when calculating the change in amount of these species.
- Some students calculated the percentage of SO_3 left at equilibrium, instead of finding the percentage of SO_3 decomposed.

B2(b)

	equilibrium partial pressure / atm			K_p / atm^{-1}
experiment	SO_2	O_2	SO_3	
1	0.38	0.44	0.12	0.227
2	0.28	2.72	0.22	0.227
3	0.28	0.39	0.22	1.58

B2(b)(i) Some O_2 was added to the equilibrium mixture in experiment 1.

As the concentration/partial pressure of O_2 was increased, the equilibrium position shifted to the right, resulting in a decrease in partial pressure of SO_2 and an increase in partial pressure of SO_3. As the change was only partially offset, the equilibrium partial pressure of O_2 was still higher than that in experiment 1.

(Note: K_p was the same for experiments 1 and 2. Hence, temperature remained unchanged.)

Comments:
- Most students correctly identified that O_2 was added to the equilibrium mixture in expt 1. However, several students incorrectly explained the shift in equilibrium position due to the increase in total pressure (caused by the addition of O_2). As only O_2 was added, the explanation should focus on how the increase in partial pressure/concentration of O_2 resulted in the shift in equilibrium position. Students need to discern between shifts in equilibrium position due to changes in concentration/partial pressure of one reactant/product versus changes in total pressure of the reaction system (due to changes in volume of the reaction vessel).
- Better answers included the explanation on why the equilibrium partial pressure of O_2 in experiment 2 is still higher than that in experiment 1 despite the shift in equilibrium position.

B2(b)(ii) The temperature of equilibrium mixture in experiment 1 was decreased.

The equilibrium position shifted to the right to favour the forward exothermic reaction. This resulted in a decrease in partial pressures of SO_2 and O_2 and an increase in partial pressure of SO_3.

(Note: K_p for experiment 3 is higher than that for experiment 1, showing that the equilibrium position lies further right for experiment 3 than for experiment 1. Also, changes such as decreasing total volume or increasing total pressure does not result in a different K_p and hence cannot result in the new equilibrium partial pressures in experiment 3.*)*

Comments:
- As the K_p of experiment 1 is different from that of experiment 3, temperature must have changed from experiment 1 to experiment 3. Some students did not realise the change in K_p and incorrectly suggested changes to total pressure/volume of the reaction system.
- A few students misread the question or mixed up the reactions in 2(a) and 2(b), and mistakenly thought the forward reaction is endothermic.

B2(b)(iii) Since the forward reaction is exothermic and produces less gaseous particles, the yield of SO_3 will be higher if the reaction is conducted under low temperatures and high pressures.

However, low temperatures will result in a slow reaction rate and high pressures will incur greater economic costs. Hence, a compromise of 400 °C and 2 atm is used industrially, together with the use of a catalyst to speed up the reaction rate.

Comments:
- In the industrial manufacture of compounds, key considerations include yield of the product, rate of production, cost and safety concerns.
- Students need to refer to the given industrial conditions in their answers and clearly explain the compromise in the temperature and pressure, as well as the role of V_2O_5 (catalyst). Note that 400 °C is not considered a low temperature and 2 atm is not considered a high pressure.

B3(a) $2MnO_4^-(aq) + 5H_2O_2(aq) + 6H^+(aq) \longrightarrow 2Mn^{2+}(aq) + 5O_2(g) + 8H_2O(l)$

Comments:
- Many students were unable to write the balanced equation between MnO_4^- and H_2O_2.
- Students need to know that
  - the reaction between MnO_4^- and H_2O_2 is a redox reaction
  - under acidic condition, MnO_4^- is reduced to Mn^{2+}. H_2O_2 is oxidised by MnO_4^- to O_2 gas

  The balanced equation can then be obtained from the reduction and oxidation half-equations from the *Data Booklet*.

B3(b) Volume of **FA 2** = $\frac{82}{10} \times 25 =$ 205 cm^3

If 25.0 cm^3 of **FA 1** were used, **205.00 cm^3** of **FA 2** solution from the burette would be required for the titration. The titration process would be very **tedious/ time-consuming** as **careful refilling** of the burette would be needed.

Comments:
- This question was generally well done.
- Students are reminded to read questions carefully. Calculation is required for the answer.

B3(c) **Calculation of volume of FA 1 used to prepare a 250 cm^3 of FA 3**

Consider the micro-titration:
10 drops of **FA 1** required 82 drops of **FA 2** for complete reaction.

Based on this micro-titration, **FA 1** needed to be diluted 8.2 times so that 25.0 cm^3 diluted solution of **FA 3** will require 25.00 cm^3 of **FA 2** for complete reaction.

Hence required volume of **FA 1** = $\frac{250}{8.2}$ = 30.49 cm^3
To prepare a 250 cm^3 solution of **FA 3**, volume of **FA 1** = 30.50 cm^3

Procedure
1. Using a burette, add 30.50 cm^3 of **FA 1** into a 250 cm^3 graduated flask.
2. Fill the graduated flask to the 250 cm^3 mark with deionised water. Use the dropping pipette (or teat pipette or dropper) to add the deionised water drop-wise when nearing the mark.
3. Stopper the graduated flask and shake the solution thoroughly to ensure that it is homogeneous. Label the solution as **FA 3**.
4. Pipette 25.0 cm^3 of **FA 3** into a 250 cm^3 conical flask and add 10.0 cm^3 of 1.0 mol dm^3 $H_2SO_4(aq)$ to it using a 10 cm^3 measuring cylinder.

5. Titrate the acidified **FA 3** solution in the conical flask with **FA 2** placed in the burette. Stop the titration when the end-point is reached i.e. when one drop of the **FA 2** added changes the colour of the solution in the conical flask from colourless to pale pink.
6. Record the titration readings using an appropriate table.
7. Repeat the titration until at least two consistent results are obtained (i.e. two titre volumes that are within 0.10 cm^3 of each other).

Key points to be included in the procedure:

✓ Apparatus used and their capacities **(A)**
- burette
- 25.0 cm^3 pipette
- 250 cm^3 graduated flask
- measuring cylinder of suitable capacity
- 250 cm^3 conical flask

✓ Preparation of **FA 3 (P)**
- add **FA 1** directly into graduated flask
- top to the 250 cm^3 mark with deionised water
- stopper and shake graduated flask well

✓ Volume of reagents (**FA3** and **FA1**) used **(V)**

✓ Volume and use of $H_2SO_4(aq)$ **(H^+)**

✓ End-point colour change **(E)**
- colourless to (pale) pink

✓ Recording of titration results and repeat titration until at least two consistent results are obtained **(R)**

Comments:
- Appropriate calculation is needed to show understanding of dilution of **FA 1** to prepare **FA 3**.
- Students are reminded to read the question carefully. The aim of the task is to find the concentration of H_2O_2 by titrating against **FA 2**, hence students need to know that **FA 2** is placed in burette.
- Vague description such as, "add a few drops of acid..." was not accepted. H_2SO_4 needs to be added in excess, and an appropriate volume must be proposed.
- Many students did not state the capacities of the conical flask (used in titration) and measuring cylinder (for measuring dil H_2SO_4).
- Some students erroneously used measuring cylinder to measure **FA 1** in the preparation of **FA 3**. In the preparation of standard solution, it is important to use a more precise apparatus to measure the volume, hence burette would be the most appropriate apparatus.
- A number of students added **FA 1** from a burette into a beaker before transferring **FA 1** from the beaker quantitatively into a graduated flask. Students should note that if the standard solution is made by dilution of a solution, the solution should be directly introduced into the graduated flask to reduce error.
- Many students were unable to give the end-point of the titration. Students are to note that the initial and final colours of the end-point needed to be clearly stated. In a titration where MnO_4^- is placed in the burette, the end-point is reached when 1 drop of MnO_4^- is unreacted, resulting in the appearance of a pale pink colour in the reaction mixture in the conical flask. As the reaction mixture in the conical flask is initially colourless, the end-point colour change is from colourless to pale pink.

B3(d)

No of mol of H_2O_2 in **25.0** cm^3 of **FA 3** = $\frac{5}{2}$ x no of mol of MnO_4^-

= $\frac{5}{2}$ x $\frac{\mathbf{y}}{1000}$ x 0.0200 = 5.00 x 10^{-5} **y** mol

No of mol of H_2O_2 in **v** cm^3 of **FA 1** = no of mol of H_2O_2 in **w** cm^3 of **FA 3**

= $\frac{\mathbf{w}}{25.0}$ x 5.00 x 10^{-5} **y** = 2.00 x 10^{-6} **wy** mol

$[H_2O_2]$ in **FA** 1 = 2.00 x 10^{-6} **wy** ÷ $\frac{\mathbf{v}}{1000}$ = 0.002 $\frac{\mathbf{wy}}{\mathbf{v}}$ mol dm^{-3}

Comments:
- Students who balanced the equation correctly in **B3(a)** were able to do this question well.

B3(e)

$2H_2O_2 \longrightarrow 2H_2O + O_2$

Vol of O_2 produced by 1 dm^3 of commercial H_2O_2 at s.t.p. = 13.4 dm^3

No of mol of O_2 produced by 1 dm^3 of commercial H_2O_2 = $\frac{13.4}{22.7}$ = 0.5903 mol

No of mol of H_2O_2 in 1 dm^3 of commercial H_2O_2 = 2 x 0.5903 = 1.181 mol

$[H_2O_2]$ = 1.18 mol dm^{-3}

Comments:
- Some students wrongly used 24 dm^3 as the molar volume in their calculations. Volume of O_2 produced is measured at s.t.p. **NOT** r.t.p. Students are reminded that the molar volume at s.t.p. and r.t.p. can be found on page 2 of the data booklet.
- Many students used the mole ratio of H_2O_2 to O_2 from the equation written in part **(a)**. This is not correct as part **(e)** does not involve MnO_4^-. The decomposition of H_2O_2 forms O_2 and H_2O as products and not H_2.

B3(f)

V_{O2} collected in the measuring cylinder is lower than V_{O2} evolved because of the following reasons (any one):

- some O_2 dissolved in the water
- some O_2 escaped before the flask is stoppered, after the mixing of the reagents
- the tubing has some water in it and some O_2 gas occupies that space previously occupied by water instead of being collected in the measuring cylinder

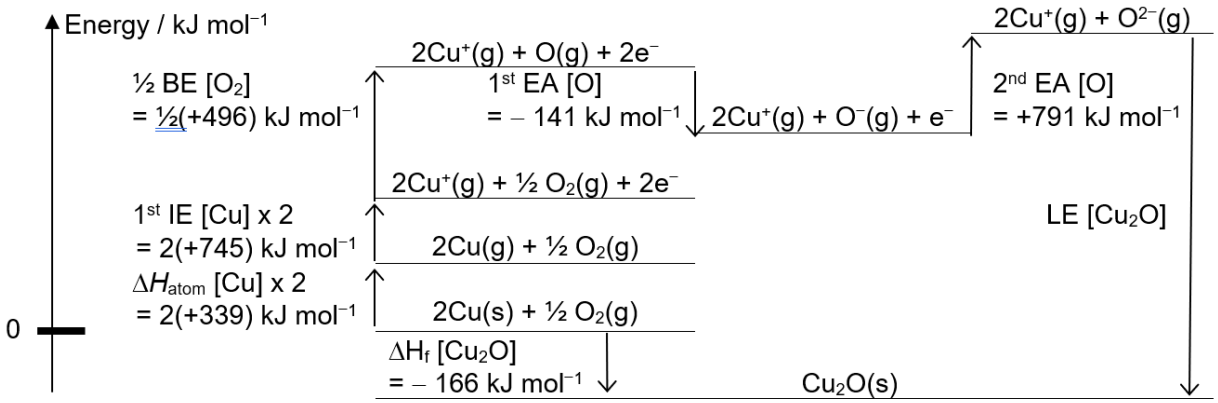
$[H_2O_2] \propto$ amount of $O_2 \propto$ volume of O_2

Since volume of O_2 collected in the measuring cylinder is lower than the actual volume of O_2 evolved, $[H_2O_2]$ determined is lower than the actual $[H_2O_2]$.

Comments:
- Most students were able to recognise that oxygen is slightly soluble in water, so that the volume of O_2 measured is less than the volume of O_2 produced.
- Students are required to relate the reason for the lower than actual amount/or volume of O_2 gas formed **AND** relate it to the concentration of $[H_2O_2]$ in the solution. While some students are able to relate this in words, it is more efficient and clearer to use the proportionality symbol '$\propto$'.

Section C

C1(a)(i)



Lattice energy of Cu_2O = −3232 = <u>−3230 kJ mol^{-1}</u>

Comments:

- Students are required to have a good understanding of the definitions of enthalpy changes. Some students did not multiply ΔH_{atom}[Cu] or 1st IE[Cu] by 2 and BE[O_2] by ½.
- Equations should be balanced in terms of charges with the correct number of électrons.
- Students are required to know that BE[O_2] is the bond energy of O=O bond and not O-O bond.
- Arrows should be drawn in the correct direction (e.g. upwards for endothermic reactions and downwards for exothermic reactions).
- The vertical axis should be drawn and labelled with 'Energy/kJ mol^{-1}' and 0 kJ mol^{-1} energy level should correspond to the elements in their standard states.
- Note that the lattice energy of an ionic compound is the energy **<u>released</u>** when 1 mole of the solid ionic compound is formed from its constituent gaseous ions under standard conditions, hence it is an exothermic reaction. Some students erroneously wrote the equation for LE as the breaking of ionic bond and obtained a positive answer.

C1(a)(ii) The experimental lattice energy of CuO is expected to <u>deviate more</u> from the theoretical value compared to that of Cu_2O. Cu^{2+} has a <u>higher charge but smaller size</u> than Cu^+ , hence Cu^{2+} has a <u>higher charge density and greater polarizing power</u> than Cu^+, leading to <u>greater covalent character in CuO</u> than in Cu_2O. The greater covalent character in CuO led to the greater deviation.

Comments:

- Students need to understand that the theoretical lattice energy is obtained based on a purely ionic model of a lattice, where all the ions are spherical and have their charge evenly distributed.
- The deviation of the experimental lattice energy from the theoretical value exists when the bonding in the ionic compounds exhibit some covalent character. When an ionic compound has a greater degree of covalent character, the greater is the deviation.
- To determine the degree of covalent character in Cu_2O and CuO, students should first compare the polarising power of Cu^+ in Cu_2O and Cu^{2+} in CuO, by considering the charge and size of cations, Cu^{2+} and Cu^+.
- Students are required to understand that the higher polarising power of the cation, the more polarised the anion will be, and thus the ionic compound will exhibit a greater degree of covalent character.
- Some students interpreted covalent character to be covalent bond and wrongly related the latter to effectiveness of orbital overlap which is irrelevant as the compounds involved are still predominantly ionic despite having some covalent character.

C1(a)(iii) q = 60.0 x 4.18 x 8.9 = +2232 J
Heat produced by reaction = <u>2232 J</u>

Amt of $Cu_2O(s)$ = 2.86 / (2 x 63.5 + 16.0) = 0.0200 mol
Cu_2O is the limiting reagent since amt of $H_2SO_4 \approx 2 \times 60 \times 10^{-3}$ = 0.12 mol

$Cu_2O(s) + H_2SO_4(aq) \rightarrow CuSO_4(s) + Cu(s) + H_2O(l)$

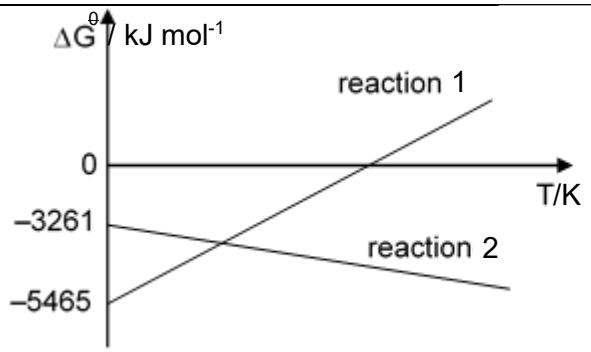
Enthalpy change of reaction = – 2232 / 0.0200 = <u>–112 kJ mol^{-1}</u>

Comments:
- Students are required to use $q=mc\Delta T$ to determine the heat change of the reaction. m is the mass of the substance (resultant solution) to which the temperature change occurs, c is the specific heat capacity of the substance (resultant solution), where it is approximated to that of water.
- To determine the enthalpy change for the reaction, students are required to use $\Delta H = -\frac{q}{n}$, where n is the amount of the limiting reagent used.

C1(b)(i) $\Delta G^{\ominus} = \Delta H^{\ominus} - T\Delta S^{\ominus}$
At 298 K,
y = – 3261 – (298)(138/1000) = <u>–3300</u> kJ mol^{-1}

Comments:
- To determine the value of $\Delta G^{\ominus}$, students are required to substitute the values of $\Delta H^{\ominus}$ and $\Delta S^{\ominus}$ given and T = 298 K into the $\Delta G^{\ominus} = \Delta H^{\ominus} - T\Delta S^{\ominus}$ equation.

C1(b)(ii)



Comments:
- Students are required to understand that a graph of $\Delta G^{\ominus}$ against temperature T is a straight line with a gradient of $-\Delta S^{\ominus}$ and a y-intercept (at 0 K) of $\Delta H^{\ominus}$. For reaction 1, $\Delta G^{\ominus}$ increases with temperature (positive gradient). For reaction 2, $\Delta G^{\ominus}$ decreases with temperature (negative gradient).
- For the command verb "Sketch", students are required to label the values of the y-intercept for both reactions 1 and 2 as given in Table 1.3.

C2(a)(i) $n(Br_2) = 3 \times 4.67 \times 10^{-9} \times 5 = 7.01 \times 10^{-8}$ mol

Assumption: The average rate is approximated to the initial rate due to the short duration of 5 s.

Comments:
- With reference to the chemical equation, students should recognise that the rate of formation of Br_2 is 3 times the rate of consumption of BrO_3^-. To determine the amount of Br_2 produced in 5 s, the rate of formation of Br_2 should be multiplied by 5.
- Quite a number of students incorrectly obtained their answer by multiplying 0.00100 by 3. This is the final concentration of Br_2 produced, not what is produced in 5 s.

- Some students overlooked the factor x 10^{-9} in the table and this resulted in an unusually large numerical answer. Students are reminded to read the headers of all tables with care.
- There were various assumptions seen in students' answers.
  The following assumptions are not valid:
  - "Rate remains constant throughout the reaction." This cannot be true as the amount of BrO_3^- decreases over time, hence the rate of consumption of BrO_3^- will decrease over time.
  - "The reaction goes to completion." Assuming that the reaction goes to completion in 5 s is very far-fetched and it also shows a poor understanding of the concept of the initial rates method.
  - "Bromine is an ideal gas." Making this assumption shows a lack of awareness of the topic being assessed in this question. In addition, this reaction is carried out in an aqueous medium. Making an assumption based on deviation from ideal gas behaviour is not valid.

  Students are strongly encouraged to review their understanding of the fundamental concepts involved in the initial rates method.

C2(a)(ii) In experiments 1 and 2, $[BrO_3^-]$ and $[Br^-]$ are constant.
When $[H^+]$ x 2, initial rate x 4,
Order of reaction with respect to H^+ is 2.

Comments:
- This question was generally well done.
- A small number of students simply stated their answer as "2" without showing any working. Students are reminded to learn to differentiate the demand of command verbs like "determine", "calculate" and "state". The former two words are more demanding and working will be expected in the answers. On the other hand, the command verb "state" is less demanding with no working required.
- Students should not use the phrase "increase by" as increasing by a factor of 2 could mean x + 2x instead of 2x.

C2(a)(iii) $[H^+]$ and $[Br^-]$ >> $[BrO_3^-]$, hence the reaction becomes a pseudo-first order reaction with respect to BrO_3^-.

rate = k' $[BrO_3^-]$ where k' = k $[H^+]^2$ $[Br^-]^b$

From experiment 3, $k' = \frac{\ln 2}{16.1} = k(0.240)^2 (0.400)^b$

From experiment 4, $k' = \frac{\ln 2}{154.2} = k(0.110)^2 (0.200)^b$

Hence, b = 1 and order of reaction with respect to Br^- is 1.

Comments:
- There were many creative attempts to show that the order of reaction with respect to BrO_3^- is 1. However, it is important to be clear in the presentation of answers. Credit was not given for ambiguous answers.
- Recognising that the reaction can be treated as a pseudo-order reaction is the key assessment point for this question. In experiments 3 and 4, $[H^+]$ and $[Br^-]$ >> $[BrO_3^-]$ (×240 and ×400 of $[BrO_3^-]$ respectively), hence expressing the rate equation as rate = k' $[BrO_3^-]$ where k' = k $[H^+]^2$ $[Br^-]^b$ will allow the order of reaction with respect to Br^- to be easily determined.

C2(a)(iv) rate = $k[H^+]^2 [Br^-] [BrO_3^-]$
Units of k = $mol^{-3}\ dm^9\ s^{-1}$

Comments:
- This question was generally well-done.
- A small number of students have not learnt how to derive the units of rate constant based on the rate equation obtained. Some students did not transfer the order of reaction with respect to H^+ to their rate equation with care. There were also students who did not include the term $[BrO_3^-]$ into their rate equation even though the question clearly stated that the order of reaction with respect to BrO_3^- is 1.
- Units of k should be written in a separate line and not next to the rate equation, as that refer to the units of rate rather than units of k.
- A common mistake was to write rate **equation**= $k[H^+]^2 [Br^-] [BrO_3^-]$, the word "equation" should not appear in the rate equation.

C2(a)(v) initial rate = $k' [BrO_3^-]$

$$= \frac{\ln 2}{16.1}(0.00100)$$

$= 4.31 \times 10^{-5}$ mol dm^{-3} s^{-1}

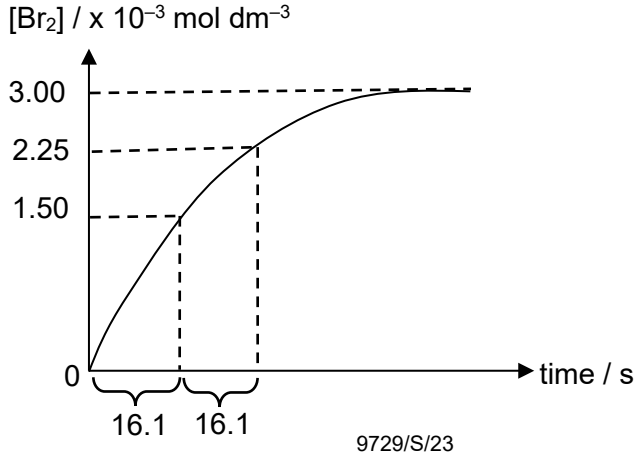
Alternative approach:
As temperature remains constant for experiments 1 to 4, k remains constant.
Using experiment 1,
rate = $k [BrO_3^-] [Br^-] [H^+]^2$
$4.67 \times 10^{-9} = k (0.001)(0.100)(0.005)^2$
k =1.868 $mol^{-3}\ dm^9\ s^{-1}$
[If experiment 2 is used, k = 1.84]

Substitute k into experiment 3.

initial rate = $1.868 (0.001)(0.400)(0.240)^2$
$= 4.30 \times 10^{-5}$ mol dm^{-3} s^{-1}

Comments:
- Recognising that the rate equation can be expressed as initial rate = $k' [BrO_3^-]$ would have allowed the initial rate to be easily determined.
- On the other hand, recognising that temperature remains constant for experiments 1 to 4, and hence the rate constant remains the same would have allowed the respective initial rates to be compared and calculated.

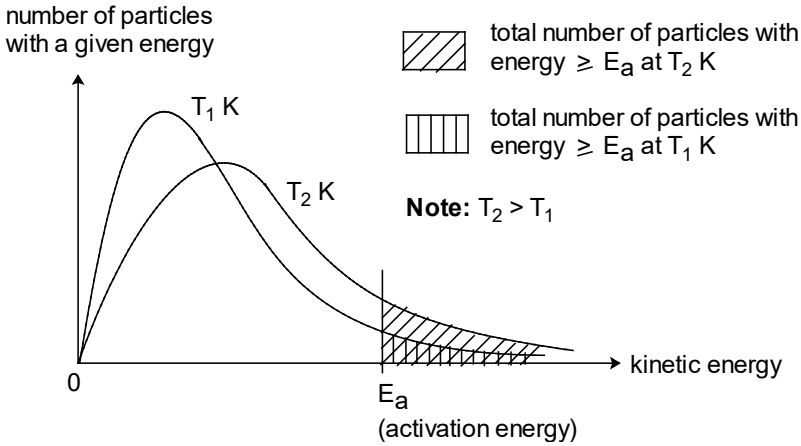
C2(a)(vi) $[Br_2] = 0.00100 \times 3 = 0.00300$ mol dm^{-3}



Comments:

- Some students did not realise that Br_2 is a product. They erroneously drew a reactant-time sketch instead.
- Others gave a straight-line sketch. This shows a lack of appreciation that it is impossible to obtain an infinite amount of Br_2, given a known amount of reactants being used.
- Labelling two half-lives and their corresponding $[Br_2]$ proved to be challenging for many students. It takes 16.1 s for ½ x (3.00×10^{-3}) = 1.50×10^{-3} mol dm^{-3} of Br_2 to be produced and it would take another 16.1 s for ¾ x (3.00×10^{-3}) = 2.25×10^{-3} mol dm^{-3} of Br_2 to be produced.
- The half-life remains at 16.1 s because it is a pseudo first order reaction where effectively only the $[BrO_3^-]$ is changing with time since $[H^+]$ and $[Br^-]$ >> $[BrO_3^-]$ and hence their concentrations do not change significantly. Even though the y-axis is $[Br_2]$, $t_{1/2} = \frac{\ln 2}{k[H^+]^2\ [Br^-]}$ and remains constant.

C2(b)



As temperature increases from T_1 to T_2 K, <u>the average kinetic energy of the reactant particles increases</u>. <u>More reactant particles have energy greater than or equal to the activation energy</u> of the reaction. This is shown by the larger shaded area at a higher temperature in the diagram above.

The <u>frequency of effective collisions increases</u>, and hence the reaction rate increases.

Comments:

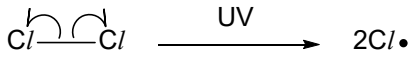
- This is a straight-forward question. Students who showed care in writing out their answers with a clearly labelled Boltzmann Distribution curve were given full credit.
- There were many answers which demonstrated limited understanding of the Boltzmann Distribution curve. Many did not pay attention to the broadening of the Boltzmann Distribution curve at a higher temperature. This feature shows a larger spread of energies with more particles having higher kinetic energy at a higher temperature. Many did not give a legend to the area under the curve where they had shaded. Others did not shade the area under the curve at the region where energy is greater than or equal to the activation energy.
- It could be observed that many students merely memorised the points deemed as needed without making reference and meaning to their Boltzmann Distribution curve.
- Better quality answers would have referred to their clearly shaded area and linked that to the number of particles having energy greater than or equal to the activation energy.
- Students are reminded that it is the frequency of effective collisions, and not the number of effective collisions, that has an impact on the rate of reaction.

C3(a)(i) Alkanes are unreactive because they <u>do not contain any region of high or low electron density</u> and thus do not attract electrophiles or nucleophiles respectively. In addition, they have relatively <u>strong C–C and C–H bonds</u> which do not break under normal conditions.

Comments:
- This question was generally well done.
- Answers that only stated that "alkanes are non-polar" without further elaboration on regions or high or low electron density were not given credit as a non-polar molecule can still contain regions of high or low electron density such as $AlCl_3$ and BF_3.
- The strength of both types of bonds in alkanes (C–C and C–H) should be discussed as the presence of only one type of strong bond does not give any indication about a molecule's reactivity.
- A small number of students was noted to have memorised the explanation without understanding, giving answers like "alkanes are unreactive because they do not contain any region of electron density".

C3(a)(ii) Free Radical Substitution

<u>Initiation</u>



<u>Propagation</u>

(a) $CH_3CH_3 + Cl\bullet \longrightarrow CH_3\underset{\bullet}{C}H_2 + HCl$

(b) $CH_3\underset{\bullet}{C}H_2 + Cl_2 \longrightarrow CH_3CH_2Cl + Cl\bullet$

then (a), (b), (a), (b) …

<u>Termination</u>

$2Cl\bullet \longrightarrow Cl_2$

$CH_3\underset{\bullet}{C}H_2 + Cl\bullet \longrightarrow CH_3CH_2Cl$

$2\,CH_3\underset{\bullet}{C}H_2 \longrightarrow CH_3CH_2CH_2CH_3$

Comments:
- This question was generally well done.
- Some answers omitted the name of the mechanism and/or both half arrows showing the homolytic fission of the $Cl{-}Cl$ bond. The half arrows should originate from the $Cl{-}Cl$ bond and end on the Cl atoms to represent the movement of electrons from the bond to the atoms. The condition of UV or heat (depending on the question context) should be indicated as this is necessary for the homolytic fission to occur and it should be written on the equation arrow and not on/under the $Cl{-}Cl$ bond.
- Students should show the lone electron on the correct atom and avoid ambiguous structure like C_4H_{10} in the termination step.
- It was also noted that some students memorised the mechanism without understanding, evident from answers that showed the free radical substitution between methane/propane (instead of ethane) with bromine (instead of chlorine).
- A small number of answers outlined the mechanism using a paragraph of words, without any chemical equation, and were not given credit.
- Some answers included wrong half arrows for the propagation steps and students should avoid including the half arrows for propagation and termination steps unless required by the question.
- Students are reminded to avoid using skeletal formula for ethane as mentioned in lecture video for Introduction to Organic Chemistry as it may be mistaken as a stray line.

C3(a)(iii) Using an excess of ethane relative to chlorine will reduce the probability of collision between chlorine radicals and chloroethane molecules. This minimizes further substitution and decreases the proportion of polysubstituted products formed.

$$CH_3CH_2Cl + Cl\bullet \longrightarrow \text{further substitution}$$

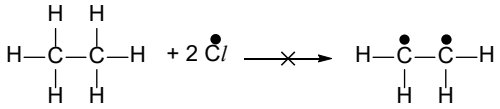
OR

If an excess of chlorine is used, it will increase the probability of collision between chloroethane molecules and chlorine radicals which will lead to further substitution and lower proportion of chloroethane formed.

$$CH_3CH_2Cl + Cl\bullet \longrightarrow \text{further substitution}$$

Comments:

- A number of students had the misconception that polysubstituted products are formed from the collision of multiple radicals with ethane at the same time. This is incorrect as disubstituted products are formed from the collision of chloroethane with 1 chlorine radical.

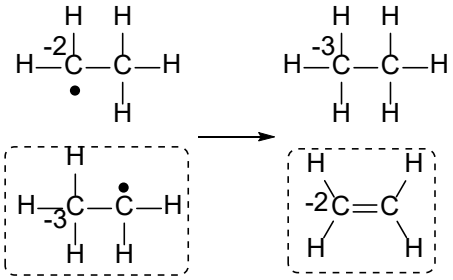


- Answers that discussed the collisions between ethane/chloroethane with chlorine molecules were not given credit as these collisions do not result in any reaction. The first propagation step involves the collision between ethane and chlorine radical (and not molecule), or for subsequent substitution, between chloroethane and chlorine radical (and not molecule).
- Answers that discussed the collisions between ethyl/chloroethyl radicals with chlorine radicals were not given credit as these collisions results in the termination of the mechanism and account only for a very small amount of chloroethane or polysubstituted products formed.
- As such, it is important to be clear when referring to species in the reaction and students should avoid ambiguous terms like “reactants”, “particles” (can refer to atoms or molecules with or without lone electron) and “chlorine” (can refer to chlorine molecule or chlorine radical).

C3(b)(i) Disproportionation

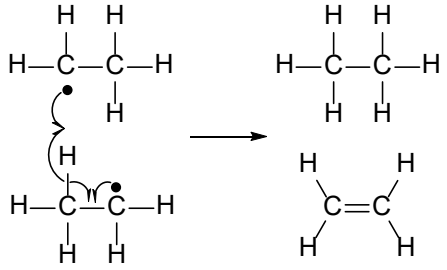
Comments:

- Oxidation number of C with lone electron decreased from −2 to −3 in ethane while the oxidation number of C of methyl group in ethyl radical increased from −3 to −2 in ethene. Hence, the ethyl radical is simultaneously oxidized and reduced.



- Students are reminded to write their answers on the given answer lines instead of empty spaces near the question.

C3(b)(ii)



Comments:

- A significant number of students were able to demonstrate good understanding of the movement of electrons by using half arrows that originate from the lone electron or C−H bond. The half arrows should end between 2 C atoms to show the formation of the π bond and between C and H to show the formation of the new C−H bond.
- For bond breaking, there are 2 electrons in the existing bond so the half arrows should account for what happens to both electrons (in this case, one is used to form new C−H bond and the other is used to form the π bond).
- For bond forming, there are 2 electrons required to form a bond so the half arrows should account for where these electrons come from (in this case, from the lone electrons and the C−H bond).

C3(b)(iii) H_2, Ni, heat / H_2, Pd / H_2, Pt

Comments:

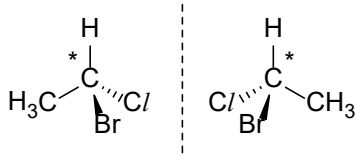
- A number of students included unnecessary conditions like “high pressure” or irrelevant specific temperatures like “300 °C” when “heat” would be sufficient.
- A small number of students omitted the condition “heat” when Nickel was used as the catalyst.
- As the question required both reagents and conditions for the reduction of alkene to form alkane, H_2 should be included in the answer.

C3(b)(iv) Cooling before <u>fractional distillation</u>

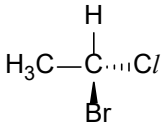
Comments:

- The compounds entering chamber 3 include gases like excess ethane, butane and chlorine from free radical substitution termination steps and chloroethane. Hence, these gases should be cooled to liquid state before using fractional distillation to separate them (analogous to the separation of oxygen and nitrogen in liquid air).
- Answers that stated only “distillation” were not given credit as the fractionating column is necessary to ensure the purity of the distillates through repeated boiling and condensation.
- Answers that described (selective) condensation were not given credit as gases do not just condense at their boiling points. If that were true, then water will only condense at 100 °C and it will not be possible to see condensed water droplets on cold drinks.

C3(c)(i)



mirror plane



wrong representation of 3D structure

Comments:

- The products of the monobromination of chloroethane are CH_2BrCH_2Cl and $CH_3CHBrCl$, and only the $CH_3CHBrCl$ is chiral.
- A small number of students showed stereochemical bonds and mirror plane for CH_2BrCH_2Cl without realising that it is achiral and that its mirror images are superimposable.
- Students should show the 3D structures of both enantiomers using stereochemical bonds in a tetrahedral shape instead of presenting them in right angles.

C3(c)(ii) 1-bromo-1-chloroethane

Comments:

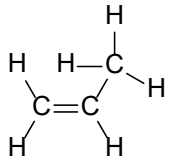
- Students are required to know that, for nomenclature, a hyphen is used to separate a letter and a number while a comma is used to separate a number and a number.
- A significant number of students made mistakes through missing or additional hyphens and/or use of commas and/or wrong order of prefix. Common mistakes (highlighted) are as follow:
  - 1-bromo,1-chloroethane (wrong use of comma to separate a letter and a number)
  - 1-bromo-1-chloro-ethane (wrong use of hyphen to separate a letter and a letter)
  - 1-chloro-1-bromoethane (wrong alphabetical order of substituents)
  - 1,1-bromochloroethane (wrong positioning of positional numbers)
  - 2-bromo-2-chloroethane (positional numbers can be smaller if numbered in another way)
- A small number of students did not realise that "systematic name" refers to the IUPAC name of the compound and gave irrelevant answers like "stereoisomers" or "enantiomers".

C3(d)(i) Constitutional/ structural isomers

Comments:

- This question was generally well done.
- A small number of students stated "cis-trans isomers" as the relationship between compounds B and C. Compounds B and C do not have the same structural formula and hence cannot be stereoisomers (cis-trans isomers). The 2 CH_2 in the structure of compound B are adjacent to each other while those in compound C are not.

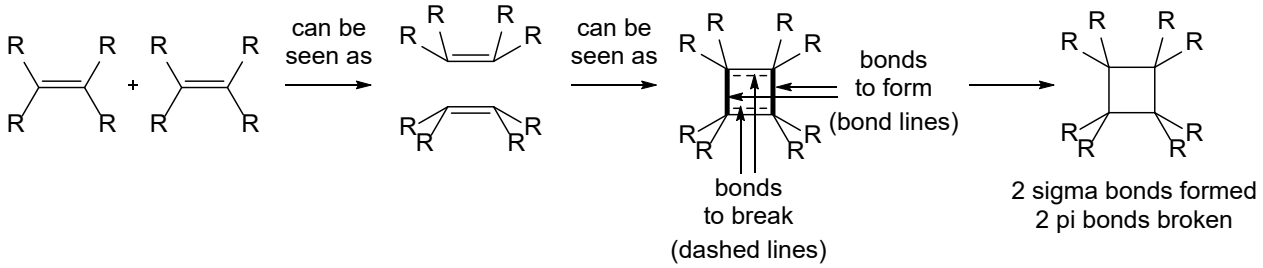
C3(d)(ii)



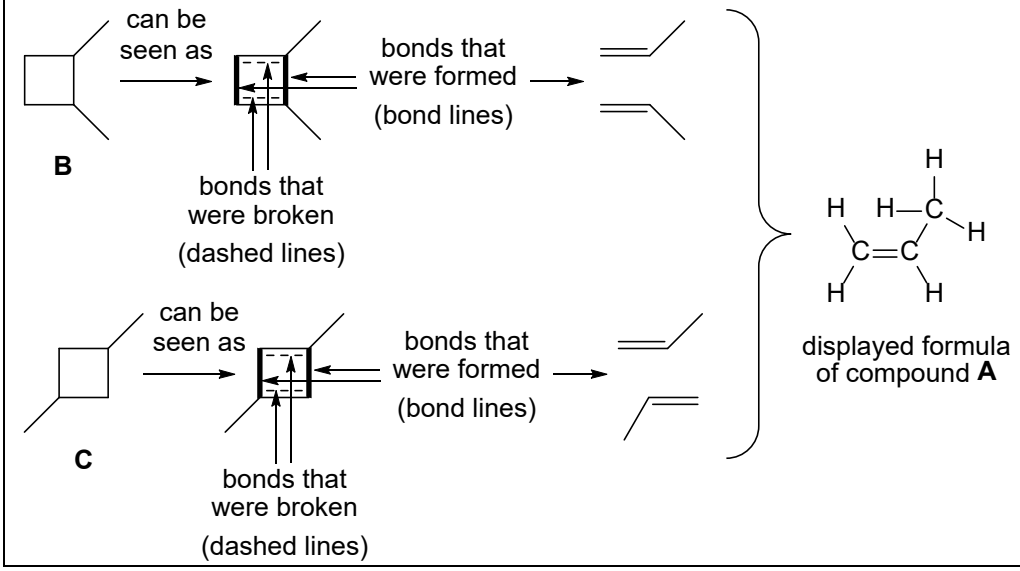
Comments:

- A significant number of students did not show all the C−H in the methyl group and hence did not show the displayed formula as required by the question.
- A small number of students drew structures containing carbon atoms with 5 bonds.
- To answer this question, students are required to recognise the pattern given in the question stem and apply the pattern.

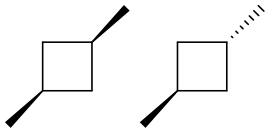
Stage 1: Pattern recognition



Stage 2: Apply the pattern



C3(d)(iii)



Comments:

- A small number of students wrongly included labels for H and/or CH_3 groups and hence did not show the skeletal formula as required by the question.
- A small number of students wrongly drew the structures of compound B and C as the answers even though both of them are constitutional isomers.

C3(d)(iv) 3

Comments:

- Students gave many different wrong answers ranging from 0 to 16.
- With 2 chiral centres in compound B, there is a maximum of $2^2 = 4$ possible stereoisomers. Note that the formula 2^{x+y} involves x chiral centres and y double bonds that give rise to cis-trans isomerism and not rings that give rise to cis-trans isomerism.
- Since there is a meso compound amongst the 4 possible structures, 2 of the structures are identical and hence there is a total of only 3 stereoisomers for compound B.