Scoring guide EOT12026S6CHEM1

April 2026
S6 END OF TERM 1
P525/1
CHEMISTRY Theory
Paper 1
2 ¾ hours

UGANDA ADVANCED CERTIFICATE OF EDUCATION
CHEMISTRY Principle Subject
Theory
PAPER 1
2 Hours 45 minutes

INSTRUCTIONS TO CANDIDATES

- This paper consists of two sections A and B. Section A consists two compulsory items.
  Write your responses to items in section A in the spaces provided
  Section B consists of two parts I and II; attempt only one item from each part.
- Write your responses to Section B on the answer sheets provided. Begin response to each item on a fresh page.
  Respond to four items in total.
- A Periodic Table is provided, refer to it whenever required.

SECTION A

Attempt all items in this section in the spaces provided

Item 1

A Ugandan petrochemical company in Jinja is at a critical decision point in planning a new production line. They must choose between producing and storing ethene (C_2H_4) for the growing plastics industry or hydrogenating it to ethane (C_2H_6) for use as a cleaner fuel additive.. Ethene is highly reactive and requires careful handling, while ethane is more stable because of its heat of formation but involves an additional hydrogenation step.

The company has been provided with the following standard heats of combustion data:

Table 1

Substance	Standard heat of combustion ($kJmol^{-1}$)
Graphite	-393.5
Hydrogen	-285.8
Ethane	-1500
Ethene	-1411

Tasks

a) Management urgently needs a complete thermochemical evaluation — including

(i) the meaning of heat of reaction and factors that affect it;

The heat of reaction (ΔH) is the enthalpy change that accompanies a chemical reaction when both reactants and products are in their standard states (298 K and 1 atm pressure). It can be positive (endothermic) or negative (exothermic).

Factors that affect the value of ΔH include:

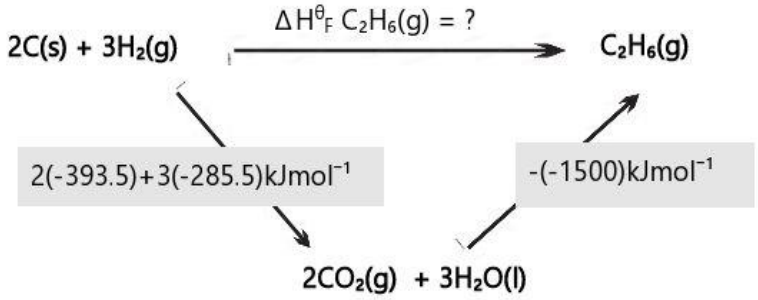
- Physical states of reactants and products
- Temperature at which the reaction is carried out
- Pressure (for reactions involving gases)
- allotropic modifications before reaction when necessary

4	3	2	1
Correctly defines heat of reaction. Identifies 4 – 3 factors affecting heat of reaction	Correctly defines heat of reaction. Identifies 2 factors affecting heat of reaction	Correctly defines heat of reaction. No factors affecting heat of reaction	Incorrectly defines heat of reaction. Identifies at least 2 factors affecting heat of reaction

(ii) An understanding of scientific laws that help in the indirect determination of heats of reaction such as in energy cycles to determine the standard heats of formation of both compounds, and hence an assessment of the relative stabilities of the two compounds and,

Hess's law states that the total enthalpy change for a reaction is the same regardless of the route taken, provided the initial and final conditions are identical. This law allows us to determine standard heats of formation indirectly using energy cycles.

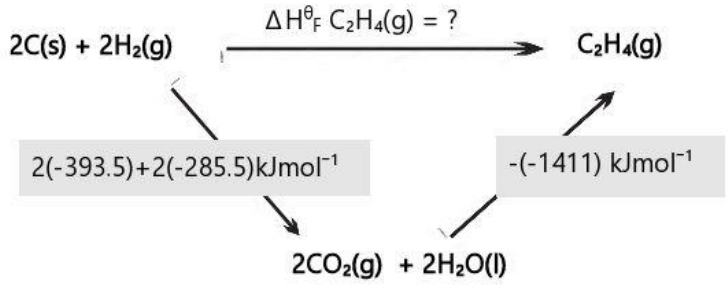
Energy cycle for ethane (C_2H_6)



By Hess's law:

$\Delta H^{\theta}_F(C_2H_6) = -1645.9 - (-1500) = -145.9\ kJ\ mol^{-1}$

Energy cycle for ethene (C_2H_4)



By Hess's law:

$\Delta H^{\theta}_F(C_2H_4) = -1358.6 - (-1411) = +52.4\ kJ\ mol^{-1}$

Relative stabilities

The more negative the value of ΔH^{θ}_{F}, the more stable the compound relative to its elements. Ethane $\Delta H^{\theta}_{F} = -145.9$ kJ mol^{-1} is therefore more stable than ethene $\Delta H^{\theta}_{F} = +52.4$ kJ mol^{-1}. Ethene is less stable and more reactive.

4	3	2	1
Correctly states Hess's law. Draws energy cycles linking heats of combustion and heats of formation for both compounds. Applies Hess's law to the energy cycles correctly. Deduces that ethane is more stable.	States Hess's law with minor omissions. Draws energy cycles linking heats of combustion and heats of formation for both compounds. Applies Hess's law to the energy cycles correctly. Deduces that ethane is more stable.	States Hess's law incorrectly. Draws energy cycles linking heats of combustion and heats of formation for both compounds but with minor errors Applies Hess's law to the energy cycles correctly. Deduces that ethane is more stable.	States Hess's law incorrectly. Draws energy cycles linking heats of combustion and heats of formation for both compounds but with minor errors Applies Hess's law to the energy cycles incorrectly.

(iii) an evaluation of the standard heat of hydrogenation of ethene — before committing to one production route.

Standard heat of hydrogenation of ethene

$C_2H_4(g) + H_2(g) \rightarrow C_2H_6(g)$

Using heats of combustion:

$\Delta H_{(hydrogenation)} = \Delta H_C$ (ethene) + ΔH_C (H_2) – ΔH_C (ethane)

$= (-1411) + (-285.8) - (-1500) = -196.8$ kJ mol^{-1}

4	3	2	1
Uses an equation of reaction and an equation relating heats of combustion and heat of reaction or draws an energy cycle relating heats	Uses an equation relating heats of combustion and heat of reaction or draws an energy cycle relating heats of combustion and heat of reaction.	Uses an equation relating heats of combustion and heat of reaction or draws an energy cycle relating heats of combustion and heat of reaction.	Uses an inverted equation relating heats of combustion Correctly substitutes and computes to the wrong answer.

of combustion and heat of reaction. Correctly substitutes and computes **–196.8 kJ mol^{-1}**	Correctly substitutes and computes –196.8 with minor omissions like the right units	Incorrectly substitutes values and gets a wrong answer.	

b) Based on the results of your analysis propose recommendations ahead of the decisive investment meeting next week.

Recommendations

On the basis of the thermochemical analysis, the company should adopt the hydrogenation route to produce ethane rather than storing ethene.

Reasons:

- Ethane has a significantly more negative heat of formation (–145.9 kJ mol^{-1}) than ethene (+52.4 kJ mol^{-1}), making it thermodynamically more stable and safer to store and handle.
- The hydrogenation step is exothermic (–196.8 kJ mol^{-1}), releasing useful energy.
- Ethene is highly reactive and requires more careful and costly storage/handling, whereas ethane is a cleaner fuel additive with lower risk.

The company should therefore invest in the hydrogenation route after confirming the economic viability of the additional step. This choice will reduce safety risks and improve long-term product stability.

4	3	2	1
Gives evidence based recommendations based on results of the analysis and relevant to the scenario	Gives evidence based recommendations based on results of the analysis but loosely relevant to the scenario	Gives generic recommendations but relevant to the scenario.	Gives generic recommendations irrelevant to the scenario.

Item 2

A pharmaceutical formulation company in Gulu is in the middle of a product-development crisis. They are scaling up production of a new oral suspension drug that uses ethoxyethane as the extraction and purification solvent. During pilot trials, the

solvent recovery step has become unreliable: boiling points of the process solutions are consistently higher than expected, leading to incomplete distillation, excessive energy consumption, product degradation, and costly production delays.

To diagnose the problem, the quality-control laboratory prepared solutions of benzoic acid (a non-volatile solute) in a fixed 150 g of ethoxyethane and measured the boiling points of each at exactly 1 atmosphere pressure.

Below is the data from their trial runs:

Table 2

Mass of benzoic acid, m (g)	5	10	15	20	25
Boiling temperature, t (°C)	35.09	35.68	36.27	36.86	37.45

Task

The production manager of the company has invited help from your A-Level Chemistry class that is on a study tour to the company to review the laboratory findings and help with:

a) A clear explanation of how a non-volatile solute affects the boiling point of a volatile solvent at constant external pressure. They also need the laboratory data to be analysed so that the ebullioscopic constant of ethoxyethane can be determined.

At constant external pressure (1 atm), a pure volatile solvent boils when its vapour pressure equals the external pressure. When a non-volatile solute (such as benzoic acid) is added, the vapour pressure of the solvent is lowered (Raoult's law) – solute particles displace some solvent molecules from the surface reducing the number escaping into the vapour phase per unit time. A higher temperature is therefore required for the vapour pressure of the solution to reach 1 atm. This results in boiling-point elevation (ΔT).

The boiling temperature t(°C) is related to the mass m(g) of the solute by the relationship:

$$t = \left(\frac{Kb}{MW}\right)m + t^{o}$$

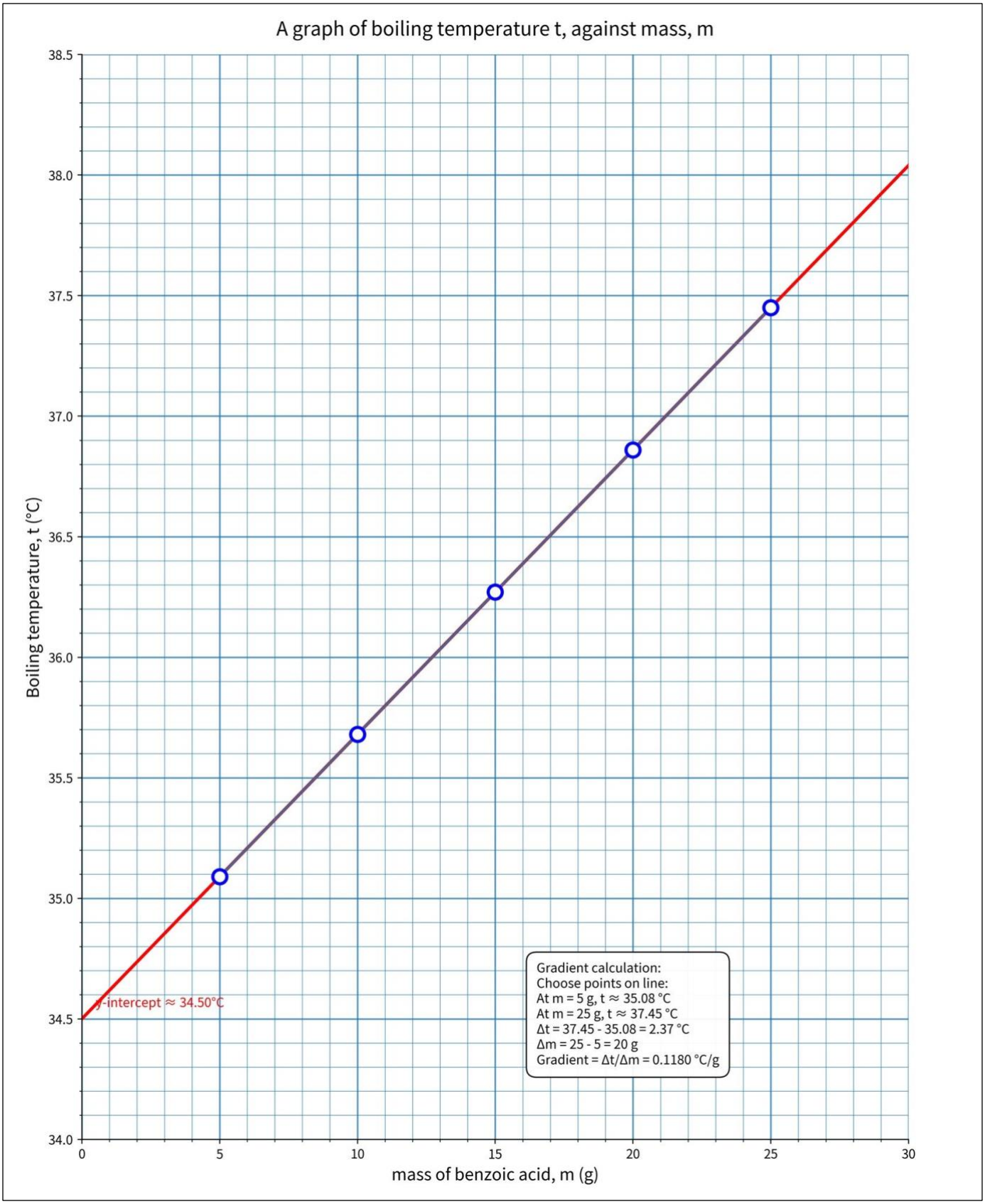
Mass of solvent W = 150 g = 0.150 kg

Molar mass of the solute, M, benzoic acid, $C_7H_6O_2$ = 12×7+1×6+16×2 = 122 $gmol^{-1}$

$$t = \left(\frac{Kb}{122 \times 0.150}\right)m + t^{o}$$

$$t = \left(\frac{Kb}{18.3}\right)m + t^{o}$$

Plotting a graph of the boiling temperature t, against the mass of benzoic acid, m will give a straight line graph with a positive gradient equal to $\frac{Kb}{18.3}$


A graph of boiling temperature t, against mass, m
Boiling temperature, t (°C)
38.5
38.0
37.5
37.0
36.5
36.0
35.5
35.0
34.5
34.0
0
5
10
15
20
25
30
mass of benzoic acid, m (g)
y-intercept ≈ 34.50°C
Gradient calculation:
Choose points on line:
At m = 5 g, t ≈ 35.08 °C
At m = 25 g, t ≈ 37.45 °C
Δt = 37.45 - 35.08 = 2.37 °C
Δm = 25 - 5 = 20 g
Gradient = Δt/Δm = 0.1180 °C/g

Gradient = 0.118 K g^{-1}

$0.118 = \left(\frac{Kb}{18.3}\right)$

$Kb = 2.16Kkgmol^{-1}$

The boiling point constant of ethoxyethane is 2.16Kkgmol^{-1} and it's boiling point when pure is 34.5°C.

4	3	2	1
Correctly explains how a non volatile solute elevates the boiling point of a volatile solvent. Derives a linear relationship between boiling point t and mass m of benzoic acid. Correctly plots a graph of t against m and determines it's gradient. Uses the gradient to get the boiling point constant of ethoxyethane.	Correctly explains how a non volatile solute elevates the boiling point of a volatile solvent. Correctly plots a graph of t against m and determines it's gradient. Uses the gradient to get the boiling point constant of ethoxyethane.	Explains how a non volatile solute elevates the boiling point of a volatile solvent with omissions or minor errors Correctly plots a graph of t against m and determines it's gradient. Uses the gradient incorrectly to get the boiling point constant of ethoxyethane.	Fails to explain how a non volatile solute elevates the boiling point of a volatile solvent. Shows poor data processing skills. Correctly plots a graph of t against m and does not get the gradient of the graph.

b) Determination of the expected boiling point of a trial solution containing 16 g of glucose dissolved in 85 g of ethoxyethane.

85g of ethoxyethane contain 16g

1 kg of ethoxyethane contains $1000 \times \left(\frac{16}{85}\right) = 188.24g$

If 12×6+1×12+16×6 = 180g of glucose in 1 kg of ethoxyethane cause an elevation in boiling point of 2.16°C, 188.24g will cause an elevation in boiling point of,

$$\left(\frac{2.16}{180}\right) \times 188.24 = 2.26°$$

Boiling point of solution = 34.50 + 2.26 = 36.76°C

4	3	2	1
Determines boiling point of pure ethoxyethane from the Y – intercept. Uses first principles to find boiling point of solution	Determines boiling point of pure ethoxyethane from the Y – intercept. Uses equation to find boiling point of solution.	Determines boiling point of pure ethoxyethane from the Y – intercept. Makes errors in computation	Does not read the Y – intercept but States the equation relating boiling point elevation and molality of the solution.

c) advise on whether they should continue with ethoxyethane or switch solvents before the next scale-up run, including any limitations of the method used and supporting reasons for your recommendation.

Ethoxyethane is advantageous because:

- It has a low boiling point – this saves on energy.
- It is relatively non toxic, making it safe for handling.
- It is a good solvent for a wide range of organic compounds so it be widely applied.

The limitations to the boiling point method used are:

- It is accurate only for dilute, ideal solutions.
- It assumes no association or dissociation of the solute in solution.
- The solute should not react with the solvent.
- Only the solvent should vaporise, the solute should be non volatile. It is not suitable for volatile solutes or high molar mass solutes like the polymers.
- It requires very precise temperature measurement (±0.01 °C).
- Results can vary with changes in external pressure.
- The solvent must be pure.

Recommendations

- Continue using ethoxyethane, but monitor non-volatile solute levels closely during recovery.
- Implement routine boiling-point checks on process solutions to predict distillation temperatures accurately.
- Consider switching to a solvent with a lower boiling point or higher Kb only if energy costs remain high.

4	3	2	1
Gives reasons why ethoxyethane is commonly used. States limitations of the boiling point method. Makes evidence based recommendations relevant to the context of the scenario.	Gives reasons why ethoxyethane is commonly used. States general limitations of colligative properties. Makes evidence based recommendations relevant to the context of the scenario.	Gives reasons why ethoxyethane is commonly used. States the general limitations of colligative properties Makes generic recommendations	Gives reasons why ethoxyethane is commonly used. States the general limitations of colligative properties Makes generic recommendations irrelevant to the context of the scenario.

SECTION B

PART I

Attempt any one item in this section

Item 3

A chemical manufacturing company is exploring new product lines to expand its portfolio. They are particularly interested in scaling up production of 2-methylpropan-2-ol for use as a high-octane fuel additive and industrial solvent. The company has received a new organic liquid Z from a potential supplier, together with combustion analysis data:

Combustion of 0.60 g of Z produced 1.32 g of CO_2 and 0.72 g of H_2O. The molecular mass of Z determined by mass spectrometry is 60. The quality control laboratory has also isolated three compounds with different boiling points from a sample of Z and labelled them U, V and W. Table 3 has data on these compounds:

Table 3

Compound	Boiling point (°C)
U	97
V	82
W	7

Management needs to understand the nature of Z, understand why Z is made of a mixture of different compounds and which of these is most suitable as a starting material for the synthesis of 2-methylpropan-2-ol (via propanone), and evaluate a viable synthesis route before committing to large-scale procurement and process development.

The production manager has invited the help of the Chemistry department in your school to review the laboratory data and submit expert recommendations ahead of the next product-line planning meeting.

Task

As a student of Chemistry on the head of department's help prepare a technical report for the production and quality-control team.

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Proposed expected response

Identification of Organic Liquid Z and Suitability for Synthesis of 2-Methylpropan-2-ol.

Prepared for: Production and Quality-Control Team

Chemical Manufacturing Company, Jinja

Date: _____

Executive Summary

Z has the molecular formula C_3H_8O and is a mixture of three structural isomers: propan-1-ol (U), propan-2-ol (V), and methoxymethane (W). Propan-2-ol (V) is the most suitable starting material for the synthesis of 2-methylpropan-2-ol via propanone. A viable two-step synthesis route is outlined. Recommendations for procurement and process development are given below.

Determination of the Molecular Formula of Z

Mass of Z = 0.60 g

Mass of CO_2 = 1.32 g; moles C = $\frac{1.32}{44}$ = 0.030 mol; mass C = 0.030 × 12 = 0.36 g

Mass of H_2O = 0.72 g ; moles H_2O = $\frac{0.72}{18}$ = 0.040 mol; moles H = 0.04 × 2 = 0.080 mol

mass H = 0.080 g

Mass of O = 0.60 – 0.36 – 0.080 = 0.16 g; moles O = $\frac{0.16}{16}$ = 0.010 mol

Mole ratio C : H : O = 0.030 : 0.080 : 0.010 = 3 : 8 : 1

Empirical formula = C_3H_8O

Given molecular mass = 60

(Empirical formula mass)n = Molecular formula mass; n is a positive whole number.

(12×3 + 1×8 + 16)n = 60; n = 1

Therefore molecular formula = $(C_3H_8O)_1$ = C_3H_8O

Why Z is a Mixture of Different Compounds

Z contains three structural (functional) isomers of C_3H_8O:

Structural isomerism is the existence of compounds with the same molecular formula but different structural formulae due to a difference in the spatial arrangement of atoms and hence bonds leading to different physical and chemical properties. The different types are chain, functional and position isomerism. U, and V are position isomers – same functional group, same longest carbon atom chains but different positions of the hydroxyl group along the chain. Methoxyethane is a functional isomer.

- U is propan-1-ol (primary alcohol) has the highest boiling point. Being a straight molecule, the molecules can pack closely increasing the effectiveness of the intermolecular forces – hydrogen bonding and Van der Waals forces in the alkyl groups.

- V is propan-2-ol (secondary alcohol) has a lower boiling point than propan – 1 – ol because its molecules are branched. The branching disrupts the intermolecular forces.
- W is methoxyethane because it has the lowest boiling point. Its molecules lack a hydroxyl group and can not associate through intermolecular hydrogen bonds, they associate through the weak Van der Waals forces that are easily overcome even at low temperatures.

These isomers have significantly different boiling points and can be separated by fractional distillation. The supplier's sample is therefore a mixture of the three isomers formed during synthesis.

Most Suitable Isomer as Starting Material

Propan-2-ol (V) is the most suitable isomer.

It can be readily oxidised to propanone (the required intermediate), whereas propan-1-ol gives propanal and methoxyethane cannot be easily converted to propanone.

Viable Synthesis Route

1. Oxidation of propan-2-ol to propanone:

$$CH_3CH(OH)CH_3 \xrightarrow[\text{Heat}]{Cr_2O_7^{2-}/H^+(aq)} CH_3CH(OH)CH_3$$

2. Grignard reaction of propanone with methylmagnesium bromide followed by hydrolysis:

$$CH_3CH(OH)CH_3 \xrightarrow{CH_3MgBr} (CH_3)_3COMgBr$$

$$(CH_3)_3COMgBr \xrightarrow{H_2O/H^+} (CH_3)_3COH + Mg^{2+} + Br^-$$

Recommendations

- Request that the supplier provides pure propan-2-ol (V) or separate the isomers by fractional distillation before use.
- Adopt the oxidation–Grignard route for large-scale production of 2-methylpropan-2-ol.
- Verify the purity of incoming Z batches using mass spectrometry.

Conclusion

Z is a mixture of C_3H_8O isomers. Propan-2-ol is the best starting material for the required synthesis. Implementing the recommended route will allow the company to expand its portfolio successfully.

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Proposed Scoring Guide

Use professional judgement for partial credit 5 | 4–3 | 2 | 1 | 0 |
Award the holistic level first, then fine-tune each cell in the basis.

Basis	Criteria
Interpretation of the scenario / task	Fully interprets the supplier data and company need; correctly determines formula of Z, recognises three isomers, explains why Z is a mixture, selects suitable isomer with reasons, and provides synthesis route and provides evidence based recommendations.
Analysis of data / application	Correctly calculates empirical formula and deduces molecular formula C_3H_8O from combustion data, matches boiling points to isomers (U = propan-1-ol, V = propan-2-ol, W = methoxyethane), with reasons based on intermolecular forces – hydrogen bonds and Van Der Waal's forces.
Logical flow of ideas	Clear sequence: formula determination ➔ identification of isomers and reason for mixture ➔ selection of suitable isomer ➔ synthesis route ➔ recommendations.
Scientific Communication	Defines all symbols used; computes to the right significant figures; indicates units for each computation; defines terms such as structural isomerism; writes organic reaction equations correctly
Recommendations	Practical, evidence-based recommendations on procurement, separation, and synthesis route, clearly linked to the analysis.

Item 4

The National Environment Management Authority (NEMA) is reviewing an application from a plastics recycling and manufacturing firm in Mukono District that plans to establish a new production line for polypropylene. The company has received two unsaturated aliphatic C_3 hydrocarbon feedstocks from industrial by-products, of

molecular masses, 42 and 40, but the identical-looking containers were accidentally mixed up during storage.
The firm also has a supply of 2-chloropropane, which they intend to convert into one of the hydrocarbons above via an elimination reaction before using it in the polymerisation step.
NEMA is particularly concerned about the environmental impact of the final plastic product, the feasibility and safety of the proposed synthetic routes (including the detailed step-by-step reaction pathway when converting 2-chloropropane to the required alkene), and whether the chosen pathway represents the most sustainable option before granting regulatory approval.
The Director of Environmental Compliance has sought for your help as head of Chemistry class in your school to analyse the situation and prepare expert advice ahead of the regulatory approval meeting.

Task

Prepare a technical report for the NEMA review panel.

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Expected learner response

Safety and Sustainability Assessment of C_3 Hydrocarbon Feedstocks for Polypropylene Production

Prepared for: NEMA Review Panel

Date: _____

Executive Summary

The two mixed-up hydrocarbons are propene (Mr = 42) and propyne (Mr = 40). Propene is the required alkene for polypropylene production. 2-Chloropropane can be converted to propene via elimination. The recommended pathway is safe, feasible, and more sustainable than using propyne. Recommendations for handling and environmental protection are provided.

Identification of the Two Hydrocarbons

The two unsaturated C_3 hydrocarbons are:

- Propene (C_3H_6, Mr = 42)
- Propyne (C_3H_4, Mr = 40)

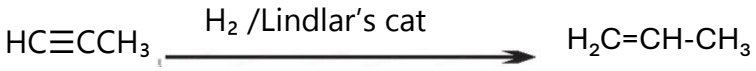
They can be distinguished by simple chemical tests: the gases are separately passed through ammoniacal silver nitrate solution at room temperature

- Propene gives no observable change
- Propyne gives a white precipitate

The containers must be relabelled immediately using these tests before any further processing.

Conversion of propyne to propene (if required)

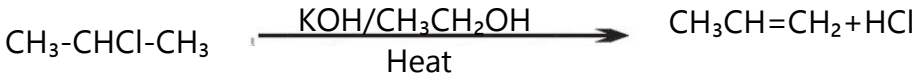
Propyne can be partially hydrogenated to propene using Lindlar's catalyst:



This step is possible but unnecessary if propene can be obtained directly from 2-chloropropane.

Synthesis of Propene from 2-Chloropropane

2-Chloropropane undergoes elimination with hot alcoholic KOH:



Mechanism (E2 elimination – step-by-step)

This is a one-step, bimolecular elimination.

Synthesis of Polypropylene from Propene

Propene undergoes addition polymerisation:

product is polypropylene, a thermoplastic widely used in packaging and construction.

Environmental Impact and Recommendations

Polypropylene is non-biodegradable and contributes to plastic pollution. However, it is recyclable.

Recommendations

- Use 2-chloropropane to produce propene via elimination – this avoids the need for propyne and is the safest, most sustainable route.
- Immediately distinguish and relabel the mixed containers using the ammoniacal silver nitrate test.
- Adopt the polymerisation route from propene for the new production line.

- Implement a closed-loop recycling programme for polypropylene waste to minimise environmental impact.
- Ensure all waste HCl from the elimination step is neutralised and disposed of responsibly.

Scoring Guide

Use professional judgement for partial credit 5 | 4–3 | 2 | 1 | 0 |
Award the holistic level first, then fine-tune each cell in the basis.

Basis	Criteria
Interpretation of the scenario / task	Fully interprets the mixed containers, the need to identify propene vs propyne, the conversion from 2-chloropropane, the polymerisation step, and environmental concerns.
Analysis of data / application	Correctly identifies propene (Mr 42) and propyne (Mr 40), gives distinguishing tests, shows elimination from 2-chloropropane with E2 mechanism, and gives addition polymerisation of propene
Logical flow of ideas	Clear sequence: identification & distinction ➔ conversion propyne to propene (if needed) ➔ synthesis of propene from 2-chloropropane (with mechanism) ➔ polymerisation ➔ environmental recommendations.
Scientific Communication	Well-organised report with headings, correct formulae and organic equations; correct curvy arrow formalism in mechanism precise terminology in describing syntheses and professional tone.
Recommendations	Evidence-based, practical recommendations (use propene route, distinguish containers, recycling programme, safe waste disposal) clearly linked to safety and sustainability.

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PART II

Attempt any one item in this section

Item 5

A group of university interns from the Department of Foods and Nutrition at Makerere University are on attachment with a local nutritional supplement company in Kampala. They have been asked to develop a new, low-cost, self-heating food warmer sachet that can be added to school feeding programmes and maternal nutrition packs in rural areas

where electricity and fuel are unreliable. The warmer works by the exothermic reaction of one of the metals listed in the data table below with water to generate enough heat to warm the food quickly and safely.

The interns have been given the following data:

Table 5

Element	Atomic number	Atomic radius (pm)	First ionisation energy (kJ mol^{-1})
Beryllium	4	112	900
Magnesium	12	160	738
Calcium	20	197	590
Strontium	38	215	550
Barium	56	222	503

They have also observed that these metals show very different rates of reaction with cold water and that beryllium behaves differently from the rest of the metals in several ways.

Before finalising the formulation, the company needs a clear scientific evaluation of these elements — including their classification in the periodic table, the reasons for the observed trends in reactivity (using the provided atomic radii and ionisation energies), a description of how each metal reacts with water to illustrate the reactivity trend, and an explanation of beryllium's anomalous behaviour — to decide which metal is most suitable for the self-heating food warmer.

The head of the internship programme has asked you to review the data and prepare expert advice for the interns ahead of their presentation to the company's product development team next week.

Task

As a student of Chemistry prepare a concise technical report for the product development team.

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Evaluation of Group 2 Metals for Self-Heating Food Warmer Sachets

Prepared for: Product Development Team

Nutritional Supplement Company, Kampala

Date: _____

Executive Summary

The five metals (beryllium, magnesium, calcium, strontium, barium) are s-block elements in group 2 of the periodic table. Reactivity increases down the group due to increasing atomic radius and decreasing first ionisation energy. Calcium is the most suitable metal for the self-heating sachet because it reacts at a moderate, controllable rate with water. Beryllium shows anomalous behaviour. Recommendations are given below.

Classification of the Elements

These elements belong to group 2A (alkaline earth metals) of the periodic table because their Valence shell has two electrons and are s-block elements because the outermost electron is in an s – subshell.

Beryllium (Be, atomic number 4):

$1s^2\ 2s^2$

Magnesium (Mg, atomic number 12):

$1s^2\ 2s^2\ 2p^6\ 3s^2$

Calcium (Ca, atomic number 20):

$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^2$

Their general outer electron configuration is ns^2 where n is the principle quantum number 1, 2, 3, 4, 5

Trends in Reactivity

Reactivity increases down the group (Be < Mg < Ca < Sr < Ba).

- In moving down the group, a full shells of electrons is successively added from one element to the next and an equal number of protons to the nucleus; both the screening effect and shielding effect increase but the screening effect outweighs the effect of the increase in nuclear charge, the effective nuclear charge on the outermost electrons decreases. So atomic radii increase (Be 112 pm ➔ Ba 222 pm). Larger atoms have valence electrons farther from the nucleus, so they are easier to remove. The first ionisation energy also decreases down the group (Be 900 kJ mol^{-1} ➔ Ba 503 kJ mol^{-1}). Less energy is required to remove the two outer s-electrons.
- Both trends make it easier for the metal to lose two electrons and form M^{2+} ions as we descend the group.

Reactions with Water to Illustrate the Trend

- Beryllium: No visible reaction with water under any conditions.
- Magnesium: Reacts very slowly with cold water, producing a few bubbles of hydrogen;

$Mg(s) + 2H_2O(l) \rightarrow Mg(OH)_2(s) + H_2(g)$

reacts more readily with hot water or steam to form magnesium oxide and hydrogen

$Mg(s) + H_2O(g) \rightarrow MgO(s) + H_2(g)$

- Calcium: Reacts steadily with cold water, producing a steady stream of hydrogen gas and forming calcium hydroxide.
  $Ca(s) + 2H_2O(l) \rightarrow Ca(OH)_2(aq) + H_2(g)$
- Strontium and barium: React vigorously with cold water, producing rapid effervescence of hydrogen and forming the corresponding hydroxides.

The increasing vigour of reaction down the group directly illustrates the increasing reactivity.

Anomalous Behaviour of Beryllium

Beryllium differs markedly from the rest of the group because of its small atomic radius, high electronegativity and hence high charge density of its ion giving it a hogh polarising power. Because of this:

- It has a much higher first ionisation energy and does not readily form Be^{2+} ions, its compounds are generally covalent.
- It does not react with water.
- Its oxide and hydroxide are amphoteric (react with both acids and bases).
- It is rendered passive by nitric acid.

These anomalies arise because beryllium is the first member of the group and has the smallest size and highest ionisation energy.

Recommendation

Calcium is the most suitable metal for the self-heating food warmer sachet. It provides a steady, controllable exothermic reaction with water, generating sufficient heat without being dangerously vigorous (unlike strontium or barium) or too slow (unlike magnesium or beryllium). Calcium is also abundant, relatively cheap, and safer to handle than the heavier group members that are toxic

Conclusion

Calcium offers the best balance of reactivity, safety, and practicality for the self-heating sachet. The company should proceed with calcium-based formulations after confirming heat output and safety in small-scale trials.

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Scoring Guide

Use professional judgement for partial credit 5 | 4–3 | 2 | 1 | 0 |

Award the holistic level first, then fine-tune each cell in the basis.

Basis	Criteria
Interpretation of the scenario / task	Fully interprets the self-heating sachet problem and addresses all required elements: classification, trends using radius & IE, reactions with water, anomalous behaviour of Be, and recommendation.
Analysis of data / application	Correctly classifies as group 2/s-block using atomic numbers and electron configurations; explains trends using given atomic radii and ionisation energies, describes reactions with water for each metal, and explains beryllium's anomalous behaviour with reasons.
Logical flow of ideas	Clear, logical sequence: classification ➔ reactivity trends (radius + IE) ➔ reactions with water (to illustrate trend) ➔ anomalous behaviour of Be ➔ recommendation. All steps linked coherently
Scientific Communication	Well-organised report with headings, correct use of data, precise terminology (s-block, screening effect, nuclear charge, ionisation energy, amphoteric, etc.), writes well balanced reaction equations to illustrate descriptions and report has a profession tone suitable for industry.
Recommendations	Evidence-based recommendation (calcium is best) clearly linked to reactivity, safety, and practicality for the food warmer.

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Item 6

A materials development company based in Namanve Industrial Park is working on a new high-performance ceramic coating for solar panels and modern construction materials. The coating must withstand very high processing temperatures, resist long-term exposure to moisture, and remain stable in mildly alkaline conditions (such as those found in cement-based building products). The research team is considering five group 14 elements — carbon, silicon, germanium, tin and lead — as the base material for the coating.

The team has been given the following group trend data:

Table 6

Element	Atomic radius (pm)	Electronegativity (Pauling Scale)	Melting point (°C)
Carbon	77	2.55	3652 (sublimes)
Silicon	118	1.90	1414
Germanium	122	2.01	938
Tin	140	1.96	232
Lead	146	2.33	328

They have also noted that the elements show different behaviours when exposed to water and alkalis, and that their oxides differ markedly in the relative stability of the +2 and +4 oxidation states down the group.

Before committing to large-scale pilot production, the company needs a clear scientific evaluation and understanding of these elements' properties to decide which one (or whose oxide) will give the best combination of high-temperature stability, resistance to water and alkalis, and long-term durability in the final coating.

The head of research has invited your A-Level Chemistry class to help review and interpret the data and prepare expert recommendations ahead of the critical product-selection meeting soon to take place.

Task

Prepare a brief but concise technical report for the research and product development team.

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Expected learner's response

Evaluation of Group 14 Elements for High-Performance Ceramic Coating

Prepared for : Research and Product Development Team

Materials Development Company, Namanve Industrial Park

Date: _____

Executive Summary

The five group 14 elements show a clear decrease in melting point after carbon, increasing metallic character, and a shift from +4 to +2 oxidation state stability down the group. Silicon (or its oxide) offers the best combination of high-temperature stability, resistance to moisture and alkalis, and long-term durability for the ceramic coating. Recommendations are given below.

Melting Point Trend

Melting points decrease sharply from carbon (3652 °C, sublimes) to tin (232 °C) and then rise slightly for lead (328 °C).

Carbon and silicon form giant covalent structures with very many strong covalent bonds due to small atoms and high electronegativity, requiring very high temperatures to melt. Down the group atomic size, increases and ionisation energy reduces, metallic character increases, leading to a change in bonding from covalent to metallic bonding which is weaker and hence lower melting points. The slight increase from tin to lead is due to poorer shielding by the d- and f-electrons, resulting in stronger metallic bonds.

Reactions with Water and Alkalis

- Carbon: Inert to both water and alkalis at room temperature but reacts with superheated steam at red heat to form a mixture of hydrogen and carbon monoxide:

  $C(s) + H_2O(g) \rightleftharpoons CO(g) + H_2(g)$
- Silicon: Does not react with water but when heated, it decomposes superheated steam to hydrogen and forms silicon(VI) oxide.

  $Si(s) + 2H_2O(g) \rightarrow SiO_2(s) + 2H_2(g)$

  It reacts slowly with hot concentrated alkalis to form silicates and hydrogen.

  $Si(s) + H_2O(g) + 2OH^-(aq) \rightarrow SiO_3^{2-}(aq) + 2H_2(g)$

Germanium, tin, and lead: react similarly; they react with hot concentrated alkalis to form germanates, stannates, and plumbates respectively, with evolution of hydrogen.

Lead has no reaction with water under normal conditions at room temperature due to its low reactivity and the formation of a protective oxide layer (PbO) in air, which inhibits further reaction. It reacts with very soft water containing dissolved oxygen (low mineral content) or slightly acidic water (e.g., pH < 7), forming soluble lead compounds like lead(II) hydroxide ($Pb(OH)_2$) or lead(II) carbonate.

$$2Pb(s) + 2H_2O(s) + O_2(g) \rightarrow 2Pb(OH)_2(s)$$

Stability of +2 and +4 Oxidation States (Using Oxides)

The relative stability of the +2 and +4 states changes down the group due to the inert pair effect.

Carbon and silicon: +4 state is much more stable (CO_2 and SiO_2 are stable; +2 oxides are reducing).

$CO(g) + PbO(s) \rightarrow CO_2(g) + Pb(s)$

$3CO(g) + Fe_2O_3(s) \rightarrow 3CO_2(g) + 2Fe(s)$

Germanium: +4 still dominant, but +2 (GeO) is known but disproportionates to germanium and germanium(IV) oxide

$2GeO(s) \rightleftharpoons Ge(s) + GeO_2(s)$

Tin: Both +2 (SnO) and +4 (SnO_2) are stable, but +4 is more stable. For example tin(II) oxide oxidises in air to tin(IV) oxide.

$2SnO(s) + O_2(g) \rightarrow 2SnO_2(s)$

Lead: +2 state (PbO) is more stable than +4, PbO_2 is a strong oxidising agent. It can oxidise concentrated hydrochloric acid to chlorine.

$PbO_2(s) + 4HCl(aq) \rightarrow PbCl_2(aq) + Cl_2(g) + 2H_2O(l)$

This trend arises because the inert pair effect (reluctance of the two s-electrons to participate in bonding) becomes more pronounced down the group due to poor shielding by d- and f-electrons.

Recommendation

Silicon (or silicon dioxide) is the most suitable material for the ceramic coating. It provides excellent high-temperature stability (melting point 1414 °C), strong resistance to moisture (forms a protective oxide layer), and good stability in mildly alkaline conditions (slow reaction only with hot concentrated alkali). Carbon is too difficult to process, while tin and lead have low melting points and poorer high-temperature performance. Germanium is too expensive. Silicon-based coatings are already proven in solar panel and construction applications and will give the best combination of durability and cost-effectiveness.

Conclusion

Silicon offers the optimal balance of properties required for the new ceramic coating. The company should proceed with silicon-based formulations after small-scale testing.

Scoring Guide

Use professional judgement for partial credit 5 | 4–3 | 2 | 1 | 0 |

Award the holistic level first, then fine-tune each cell in the basis.

Basis	Criteria
Interpretation of the scenario / task	Fully interprets the coating requirements (high temperature, moisture resistance, alkaline stability) and addresses melting point trend, reactions with water/alkalis, +2/+4 stability using oxides, and gives a clear recommendation.
Analysis of data / application	Correctly explains melting point trend using given data, describes reactions with water and alkalis, and uses oxides to explain the shift from +4 to +2 stability down the group (inert pair effect).
Logical flow of ideas	Clear, logical sequence: melting point trend explained coherently from cause to effect ➔ reactions with water/alkalis linked to moisture / alkalis resistance ➔ oxidation state stability ➔ recommendation based on coating requirements. All steps linked coherently.
Scientific Communication	Well-organised report with headings, correct use of data, precise terminology (inert pair effect, giant covalent structure, metallic character), use of well balanced chemical equations of reaction, and a professional tone.
Recommendations	Evidence-based recommendation (silicon or SiO_2 is best) clearly linked to the analysed properties and the company's coating needs.

END