Tr JoelPCM Academic Council

Advanced Secondary Curriculum — ASC

CHEMISTRY

PAPER 1 — THEORY | SET IV

2 Hours 45 Minutes

Candidate Name: _____ Index No: _____

Centre Name: _____ Year: 2026

INSTRUCTIONS TO CANDIDATES

1. Do not open this booklet until you are told to do so.
2. Write your name, index number and centre in the spaces provided above.
3. Answer BOTH compulsory items in Section A (Items 1 and 2).
4. In Section B Part I, answer ONE item from Items 3 and 4.
5. In Section B Part II, answer ONE item from Items 5 and 6.
6. All answers must be written in the spaces provided in this booklet.
7. Where applicable, show ALL working clearly.
8. The use of a silent, non-programmable scientific calculator is permitted.
9. Atomic masses: H=1; C=12; N=14; O=16; Cl=35.5; Br=80; Mg=24; Ni=58; Sn=119; Pb=207

ASSESSMENT OBJECTIVES AND TOPICS

Section A (Compulsory):

Item 1 (AO3): Moles & Equations — Isotopes, Mass Spectrometry, Relative Atomic Mass

Item 2 (AO4): Equilibria & Electrochemistry — Redox Reactions, Half Equations, Oxidation States

Section B Part I (attempt ONE):

Item 3 (AO1): Atomic & Electronic Structure | Bonding & Structure | Periodicity I & II

Item 4 (AO1): Atomic & Electronic Structure | Bonding & Structure | Periodicity I & II

Section B Part II (attempt ONE):

Item 5 (AO2): Organic Chemistry I | Organic Chemistry II | Organic Chemistry III

Item 6 (AO2): Organic Chemistry I | Organic Chemistry II | Organic Chemistry III

SECTION A — Answer BOTH compulsory items

Item 1

Assessment Objective 3 (AO3) — Compulsory

Topics Assessed:
Moles & Equations | Isotopes | Relative Atomic Mass

The National Isotope Analysis Centre (NIAC) in Nairobi, Kenya, is a government-funded laboratory that uses mass spectrometry to determine the isotopic composition of metals used in pharmaceutical manufacturing, industrial alloys, and environmental monitoring. The centre recently received three samples for analysis: a sample of magnesium (Mg) from a fertiliser company, a sample of nickel (Ni) from a mining corporation, and a sample of chlorine-containing gas from a chemical plant. The mass spectra and isotopic data collected by the instrument operators are presented in Tables 1.1, 1.2, and 1.3, and in Figure 1.1.

Table 1.1 — Mass spectrum data for the magnesium sample

m/z value	24	25	26
Relative Intensity	1	0.127	0.139

Table 1.2 — Isotopic data for naturally occurring magnesium (RAM = 24.3)

Isotope	Mg-24	Mg-25	Mg-26
Mass Number	24	25	26
% Abundance	?	?	?

Table 1.3 — Mass spectrum data for the nickel sample

Relative Abundance	69	27	4
m/z value	58	60	62

Figure 1.1 — Mass spectrum for the chlorine-containing gas sample (Cl_2 molecular ions)

The spectrum shows peaks at the following m/e values:
m/e = 35 and 37 (atomic ion region, labelled A-B on spectrum)
m/e = 70 (tallest molecular ion peak)
m/e = 72 (second molecular ion peak)
m/e = 74 (smallest molecular ion peak)
Peaks at 35 and 70 are the tallest in their respective regions.

Additional data provided by the chemical plant:

• When chloromethane (CH_3Cl) is analysed separately in the mass spectrometer, two peaks are observed with an abundance ratio of 3:1.
• A sample of C_2H_5Cl was also submitted. Its mass spectrum shows peaks corresponding to ^{1}H, ^{2}H, ^{12}C, ^{13}C, ^{35}Cl and ^{37}Cl.

Task

You are a senior mass spectrometry analyst at NIAC. Write a full analytical report addressing ALL of the following:

(a) Define the following terms as used in mass spectrometry and atomic structure:
(i) Atomic number
(ii) Mass number
(iii) Relative atomic mass
(iv) Isotope

(b) Using Table 1.1 (magnesium sample):
(i) Explain why magnesium gives THREE peaks in its mass spectrum.
(ii) Calculate an accurate value for the relative atomic mass of magnesium using the data in Table 1.1. Show all working.

(c) Using Table 1.2 and the known RAM of magnesium (24.3):
The percentage abundance of Mg-24 is EIGHT TIMES that of Mg-26. Calculate the percentage abundance of each magnesium isotope in the sample. Show all steps clearly.

(d) A mass spectrometer measures the relative abundance of ions with different values of m/z. Explain clearly what the symbols m and z represent in the context of mass spectrometry.

(e) Using Table 1.3 (nickel sample):
(i) Write the full symbol (including mass number and atomic number) for the ion responsible for the peak at m/z = 58.
(ii) Calculate the relative atomic mass of this sample of nickel. Show all working.

(f) Using Figure 1.1 (chlorine sample):
(i) State the ions responsible for each of the peaks at m/e = 35, 37, 70, 72, and 74.
(ii) Explain why the peaks at m/e = 35 and m/e = 70 are relatively taller than the other peaks in their respective regions.
(iii) Use the spectrum to calculate the relative atomic mass of chlorine. Show your working.
(iv) Chloromethane (CH_3Cl) analysed separately gives two peaks in a ratio of 3:1. Explain this observation.

(g) For the C_2H_5Cl sample (isotopes ^{1}H, ^{2}H, ^{12}C, ^{13}C, ^{35}Cl, ^{37}Cl):
(i) Calculate the mass number of the most abundant molecular ion.
(ii) Calculate the mass number of the heaviest possible molecular ion.

(iii) Write the formulae of ALL possible ions that contribute to a peak at a mass number of 66.

Item 2

Assessment Objective 4 (AO4) — Compulsory

Topics Assessed:
Equilibria II | Electrochemistry | Redox Reactions

Smeltech Mining Corporation, headquartered in Ndola, Zambia, operates a lead processing facility where lead(IV) oxide (PbO_2) is produced as an intermediate in the refining of lead ore. The compound PbO_2 is also used in the company's lead-acid battery manufacturing unit. The quality control team has been investigating two chemical reactions involving PbO_2 that are critical to production: (i) its reaction with concentrated hydrochloric acid, and (ii) its ability to oxidise manganese(II) sulphate in the presence of concentrated nitric acid. The relevant data are given below.

Table 2.1 — Standard electrode potentials relevant to the investigation

Half-reaction	E° (V)
$PbO_2(s) + 4H^+(aq) + 2e^- \rightarrow Pb^{2+}(aq) + 2H_2O(l)$	+1.46
$Cl_2(g) + 2e^- \rightarrow 2Cl^-(aq)$	+1.36
$MnO_4^-(aq) + 8H^+(aq) + 5e^- \rightarrow Mn^{2+}(aq) + 4H_2O(l)$	+1.51
$2H^+(aq) + 2e^- \rightarrow H_2(g)$	0.00

Experimental Observations recorded by the quality control team:

Experiment A: When PbO_2 was added to concentrated hydrochloric acid and gently warmed, a reddish-brown gas was evolved and the solution turned colourless.
Experiment B: When PbO_2 was added to a solution of manganese(II) sulphate in the presence of concentrated nitric acid, a colour change was observed in the solution.

Task

You are the lead chemist at Smeltech Mining Corporation writing a technical report on the reactivity of lead(IV) oxide. Your report must address ALL of the following:

(a) For Experiment A — Reaction of PbO_2 with concentrated HCl:

(i) Identify the reddish-brown gas evolved and explain what this tells you about the role of PbO_2 in the reaction.

(ii) State the conditions required for this reaction to proceed.

(iii) Write the balanced reduction half-equation for PbO_2 acting as an oxidising agent in this reaction.

(iv) Write the balanced oxidation half-equation for Cl^- being oxidised.

(v) Combine the half-equations to write the overall balanced ionic equation for the reaction.

(b) For Experiment B — Reaction of PbO_2 with $MnSO_4$ in conc. HNO_3:

(i) State what colour change was observed in Experiment B and identify the product formed.

(ii) Write a balanced equation for the reaction that took place, showing clearly which species is oxidised and which is reduced.

(iii) Using the electrode potential data in Table 2.1, explain why PbO_2 is able to oxidise Mn^{2+} to MnO_4^- under these conditions.

(c) Lead(IV) oxide is described as a strong oxidising agent.

(i) Using the electrode potential data, confirm that PbO_2 can oxidise Cl^- to Cl_2. Calculate the e.m.f. for this reaction.

(ii) Explain what happens to the oxidation state of lead in Experiment A and deduce the change in oxidation state of chlorine. Hence confirm that PbO_2 is acting as an oxidising agent.

(d) In the lead-acid battery, PbO_2 is used as the cathode material. During discharge:

(i) Write the half-equation for the reduction of PbO_2 at the cathode during discharge.

(ii) Explain why PbO_2 is suitable for use as a cathode material in an acidic electrolyte battery, referring to its electrode potential.

SECTION B — PART I (AO1): Answer ONE item only

Topics: Atomic & Electronic Structure | Bonding & Structure | Periodicity I & II

Item 3

Assessment Objective 1 (AO1) — Attempt 1 of 2

Topics Assessed:
Bonding & Structure | Periodicity I | Periodicity II

A materials engineering research centre at the University of Dar es Salaam is conducting a comparative study of Group IV elements — carbon (C), silicon (Si), germanium (Ge), and tin (Sn) — to evaluate their suitability for use in semiconductor devices, structural alloys, and industrial catalysts. The research team is analysing the bonding, molecular geometry, and chemical reactivity of these elements and their compounds. The data collected are presented in Tables 3.1 and 3.2.

Table 3.1 — Bond energies of Group IV element-element single bonds

Bond	C–C	Si–Si	Ge–Ge	Sn–Sn
Bond Energy (kJ mol^{-1})	346	175	168	156

Table 3.2 — Properties of selected Group IV compounds

Compound	Central Atom	Bonding Type	Expected Shape	Bond Angle
CO_2	C	Covalent (double bonds)	?	?
SiO_2	Si	Giant covalent network	?	?
CCl_4	C	Covalent	?	?
CH_4	C	Covalent	?	?
CS_2	C	Covalent (double bonds)	?	?
SnO_3^{2-}	Sn	Ionic/Covalent	?	?

Task

You are the lead research chemist at the university. Write a comprehensive technical report addressing ALL of the following:

(a) Using Table 3.1:

(i) State and explain the trend in bond energy from C–C to Sn–Sn.

(ii) Explain how bond energy affects the tendency of these elements to catenate (form long chains of the same element). Which element has the greatest tendency to catenate and why?

(b) Draw the structures and name the shapes of ALL the species in Table 3.2. Complete the table with your answers. For each species use VSEPR theory to predict the shape.

(c) Using your answer in (b):

(i) Briefly explain why CO_2 adopts the shape you have named, referring to electron pair repulsion theory.

(ii) Compare the bond angle of CS_2 and SnO_3^{2-}. Give a reason for the difference in bond angles.

(d) The elements carbon, silicon, germanium, and tin react differently with concentrated hydrochloric acid. Describe these reactions, writing equations where reactions occur.

(e) Write an equation for the formation of silane (SiH_4) from silicon.

(f) The elements tin and lead belong to Group IV. Describe the reactions of tin and lead with:

(i) Water

(ii) Concentrated sulphuric acid

(iii) Alkalis (NaOH solution)

Write equations where reactions occur and state any special conditions required.

Item 4

Assessment Objective 1 (AO1) — Attempt 1 of 2

Topics Assessed:
Atomic & Electronic Structure | Bonding & Structure | Periodicity I & II

An industrial chemistry institute in Kigali, Rwanda, is carrying out a systematic investigation into the chemistry of Group IV elements — particularly carbon (C) and silicon (Si) — in preparation for developing new carbon-capture technologies, silicon-based materials, and tin-based industrial reagents. The research team has designed a series of experiments to study the reactivity of carbon and silicon under different chemical conditions, and to investigate the preparation and properties of tin chlorides.

Background data provided to the research team:
- Carbon exists in several allotropic forms including diamond, graphite, and graphene.
- Silicon forms a giant covalent structure similar to diamond.
- Tin forms two chlorides: tin(II) chloride ($SnCl_2$) and tin(IV) chloride ($SnCl_4$).
- Tin(IV) bromide does NOT exist under normal conditions.

Task

You are the lead inorganic chemist at the institute. Write a detailed technical report addressing ALL of the following:

(a) State the conditions and write balanced equations for the reaction between carbon and:

(i) Water (steam)

(ii) Concentrated sulphuric acid

(b) Compare the reactions of carbon and silicon with:

(i) Concentrated nitric(V) acid

(ii) Concentrated sodium hydroxide solution

In each case, state whether a reaction occurs, write an equation if it does, and explain any difference in reactivity between carbon and silicon.

(c) Tin forms two chlorides — $SnCl_2$ and $SnCl_4$. State how each of the following can be prepared:

(i) Tin(II) chloride, $SnCl_2$

(ii) Tin(IV) chloride, $SnCl_4$

In each case write an equation for the preparation reaction.

(d) Tin(IV) chloride exists as a stable compound, but tin(IV) bromide does NOT exist under normal conditions. State TWO reasons that account for this difference.

(e) Lead(IV) oxide (PbO_2) reacts with hydrochloric acid by a redox reaction.

(i) State the conditions for this reaction.

(ii) Write the reduction and oxidation half-equations for this redox reaction.

(iii) Hence write the overall balanced equation.

(f) Lead(IV) oxide was added to a solution of manganese(II) sulphate in the presence of concentrated nitric acid.

(i) State what was observed.

(ii) Write the balanced equation for the reaction that took place.

SECTION B — PART II (AO2): Answer ONE item only

Topics: Organic Chemistry I | Organic Chemistry II | Organic Chemistry III

Item 5

Assessment Objective 2 (AO2) — Attempt 1 of 2

Topics Assessed:
Organic Chemistry I | Organic Chemistry II | Organic Chemistry III

A pharmaceutical research company, BioSynth Rwanda Ltd in Kigali, is investigating two unknown organic compounds — Compound H and Compound J — isolated from fermentation extracts and submitted for structural identification. The analytical chemistry department has conducted combustion analysis, vapour density experiments, and a series of chemical characterisation tests. The experimental findings are presented below.

Compound H — Combustion and chemical test data:

Elemental composition of H: 22.86% oxygen, 8.57% hydrogen, the rest being carbon.
When 0.30 g of H is vapourised at 80 °C and 134.77 cm³, the vapour behaves as an ideal gas.
Chemical tests:

- H forms a yellow precipitate with 2,4-dinitrophenylhydrazine (2,4-DNPH).
- H does NOT react with Tollens' reagent (ammoniacal silver nitrate).

Compound J — Molecular formula and reaction data:

Molecular formula of J: $C_3H_4Br_2$
Reaction 1: When J was heated with sodium metal in ethanol, compound K was formed.
Reaction 2: K reacts with water in the presence of sulphuric acid and mercurous sulphate at 60 °C to form compound L.
Chemical tests on L:

- L does NOT react with Fehling's solution.
- L forms a yellow precipitate with 2,4-dinitrophenylhydrazine.

Task

You are the analytical chemist at BioSynth Rwanda. Write a full structural identification report addressing ALL of the following:

COMPOUND H:

(a) (i) Using the percentage composition data, calculate the empirical formula of H.

(ii) When 0.30 g of H is vapourised at 80 °C and 134.77 cm³, determine the molecular formula of H. (Use ideal gas assumptions: molar volume at 80°C/1atm ≈ 27.9 $dm^3\ mol^{-1}$, or use PV=nRT.)

(b) H forms a yellow precipitate with 2,4-DNPH but does NOT react with Tollens' reagent. Identify the functional group present in H and hence identify compound H by name and structural formula.

(c) Write the equation for the formation of the yellow precipitate when H reacts with 2,4-DNPH.

COMPOUND J:

(d) Write down the structural formulae and IUPAC names of ALL possible structural isomers of J ($C_3H_4Br_2$).

(e) When J is heated with sodium metal in ethanol, compound K is formed.

(i) Write the equation and suggest the mechanism for the reaction between J and sodium metal in ethanol.

(ii) K reacts with water in the presence of H_2SO_4 and $HgSO_4$ at 60 °C to form compound L. L does NOT react with Fehling's solution but forms a yellow precipitate with 2,4-DNPH. Name and give the structural formula of compounds K and L. Explain the role of $HgSO_4$ in the reaction.

(f) Write the equation and suggest the mechanism for the reaction between L and 2,4-dinitrophenylhydrazine.

Item 6

Assessment Objective 2 (AO2) — Attempt 1 of 2

Topics Assessed:
Organic Chemistry I | Organic Chemistry II | Organic Chemistry III

An organic chemistry laboratory at Makerere University in Kampala is conducting research into reaction pathways of oxygenated organic compounds. The team is investigating a series of inter-connected reaction schemes involving a C_3H_8O isomer and a $C_5H_{12}O$ compound. The experimental data from both investigations are presented below.

Investigation A — Reaction chain starting from a C_3H_8O compound (compound M):

M is one of the isomers of C_3H_8O.
M reacts with acidified potassium dichromate ($K_2Cr_2O_7/H^+$) to form compound N.
N reacts with phosphorous pentachloride (PCl_5) to form compound P.
P is hydrolysed with aqueous sodium hydroxide on heating to form compound Q.
Q forms a yellow precipitate with iodine solution and sodium hydroxide solution (positive iodoform test).

Investigation B — Compound R synthesis from S and T:

$CH_3CH_2CHO \xrightarrow{\text{(Step II)}} S$
$CH_3COCH_3 \xrightarrow{\text{(Step I)}} T$
$S + T \xrightarrow{\text{(Step III)}} CH_3CH_2COCH(CH_3)_2$ [Compound R]

Additional information: R can be synthesised by the reaction between S and T.

Investigation C — Compound V (molecular formula $C_5H_{12}O$):

V reacts with sodium metal to form hydrogen gas.
$V \rightarrow$ (conc. H_2SO_4, heat) $\rightarrow X$
$V \rightarrow$ ($K_2Cr_2O_7/H^+$, heat) $\rightarrow W$
$X \rightarrow$ (1. O_3/CCl_4, <20°C; 2. $Zn/H_2O/CH_3COOH$) $\rightarrow CH_3CH_2CHO + CH_3CHO$
W reacts with phenylhydrazine and gives a positive iodoform test.

Task

You are the research organic chemist at Makerere University. Write a comprehensive analysis report addressing ALL of the following:

INVESTIGATION A — C_3H_8O reaction chain:

(a) Write the structural formulae and IUPAC names of ALL possible isomers of C_3H_8O.

(b) Using the reaction chain above, identify compounds M, N, P and Q, giving the name and structural formula of each. Justify your identification by explaining each step in the chain and the significance of the iodoform test result for Q.

(c) Write the equation and indicate the mechanism for the reaction between compound M and concentrated sulphuric acid.

(d) Describe a simple chemical test that could be used to distinguish between propane (C_3H_8) and propanal (C_2H_5CHO). State the reagent(s), what you would do, and the expected observations for each compound.

INVESTIGATION B — Compound R synthesis:

(e) (i) Identify compounds S and T.

(ii) Name the type of reaction that occurs in Step I and Step II.

(f) Identify the reagents and state the conditions necessary for:

(i) Step I ($CH_3COCH_3 \rightarrow$ T)

(ii) Step III (S + T $\rightarrow$ R = $CH_3CH_2COCH(CH_3)_2$)

(g) Write the mechanism for the reaction that occurs in Step III.

INVESTIGATION C — Compound V ($C_5H_{12}O$):

(h) V reacts with sodium metal to form hydrogen gas. What functional group does this confirm is present in V?

(i) The ozonolysis of X (from V via conc. H_2SO_4) gives CH_3CH_2CHO and CH_3CHO. Use this information to determine the structure of X and hence the structure and IUPAC name of V.

(j) W (from oxidation of V) reacts with phenylhydrazine and gives a positive iodoform test. Identify W and confirm whether your structure of V is consistent with these observations.

END OF PAPER

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