Diploma Programme
Programme du diplôme
Programa del Diploma

Chemistry
Higher level
Paper 2

19 May 2025

Zone A morning | **Zone B** morning | **Zone C** morning

Candidate session number

2 hours 30 minutes

Instructions to candidates

- Write your session number in the boxes above.
- Do not open this examination paper until instructed to do so.
- Answer all questions.
- Answers must be written within the answer boxes provided.
- A calculator is required for this paper.
- A clean copy of the **chemistry data booklet** is required for this paper.
- The maximum mark for this examination paper is **[90 marks]**.

2225 – 6215

19 pages

Answer **all** questions. Answers must be written within the answer boxes provided.

1. Hydrogen cyanide, HCN, is a very toxic compound.

(a) Pure HCN is a volatile liquid, boiling at 26 °C.

(i) Draw the Lewis formula of the HCN molecule. [1]

(ii) Deduce the hybridization of the carbon atom and the number of sigma and pi bonds that it forms. [2]

Hybridization: . . . . . .

Sigma bonds: . . . . . .

Pi bonds: . . . . . .

(iii) State and explain the molecular geometry of HCN without referring to hybridization. [2]

Molecular geometry: . . . . . .

Explanation: . . . . . .

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(iv) HCN is a polar molecule. Deduce which atom carries a partial positive charge and which carries a partial negative charge. [1]

Partial positive charge: . . . . . .

Partial negative charge: . . . . . .

(This question continues on the following page)

(Question 1 continued)

(v) Explain why nitrogen gas, N_2, has a much lower boiling point than HCN. [2]

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(b) HCN acts as a weak acid in aqueous solution.

(i) Write an equation to show this behaviour. [1]

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(ii) Outline **two** ways in which you could determine that a solution was $0.1\,mol\,dm^{-3}$ HCN rather than $0.1\,mol\,dm^{-3}$ HCl. [2]

Method 1: . . . . . .

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Method 2: . . . . . .

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(iii) Calculate the pH of a $0.100\,mol\,dm^{-3}$ solution, given the K_a of HCN is $4.90 \times 10^{-10}\,mol\,dm^{-3}$. [2]

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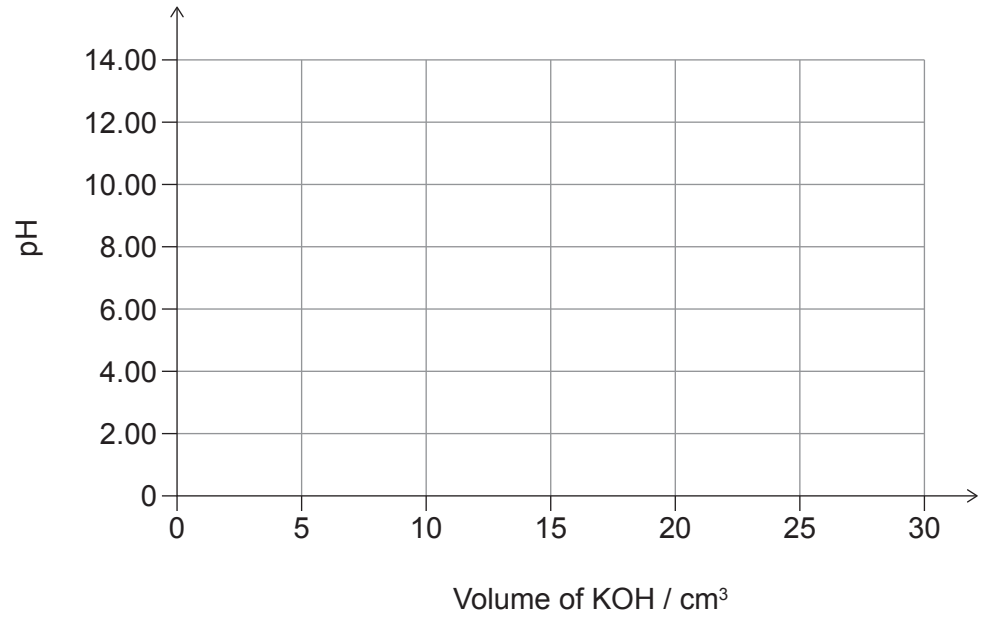
(This question continues on the following page)

(Question 1 continued)

(iv) Sketch the variation in pH that would occur if 30.0 cm^3 of 0.200 mol dm^{-3} KOH was gradually added to 20.0 cm^3 of 0.100 mol dm^{-3} HCN. [3]



(v) Deduce the point on the graph in (b)(iv) at which the solution would only contain KCN (aq) and label it "Salt". [1]

(vi) Calculate the temperature rise of the solution when 30.0 cm^3 of 0.200 mol dm^{-3} KOH is mixed with 20.0 cm^3 of 0.100 mol dm^{-3} HCN. Use enthalpy of neutralization of HCN = –13.3 kJ mol^{-1} and sections 1 and 2 of the data booklet. [2]

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(This question continues on the following page)

(Question 1 continued)

(c) The cyanide ion, CN^-, can form complex ions, such as $[Fe(CN)_6]^{4-}$.

(i) State the precise type of bond formation between the cyanide ion and the iron ion. [1]

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(ii) Deduce the oxidation state of iron in the complex ion. [1]

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(iii) Explain why transition element ions, such as $[Fe(CN)_6]^{4-}$, are usually coloured. [3]

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(iv) $[Fe^{2+}]$ is $2.20 \times 10^{-7}\,mol\,dm^{-3}$ in a $1.00\,mol\,dm^{-3}$ solution of the complex ion.

Determine the value of the equilibrium constant, *K*, for the formation of $[Fe(CN)_6]^{4-}$ from its constituent ions. [3]

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(Question 1 continued)

(v) Outline, giving a reason, whether $[Fe(CN)_6]^{3-}$ is a stronger or weaker oxidizing agent than $Fe^{3+}(aq)$.

Use $E^{\ominus}$ $[Fe(CN)_6]^{3-}(aq) + e^- \rightleftharpoons [Fe(CN)_6]^{4-}(aq) = +0.37\,V$ and section 19 of the data booklet. [2]

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(d) The cyanide ion reacts with iodomethane, CH_3I.

(i) Draw the structural formula of the organic product. [1]

(ii) Predict, giving a reason, whether this reaction will occur by an S_N1 or S_N2 mechanism. [1]

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(iii) Explain how you might **experimentally** conclude whether the mechanism of this reaction is S_N1 or S_N2. [2]

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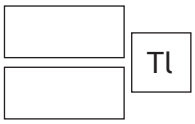
2. Thallium is a heavy metal in group 13 of the periodic table.

(a) 30 % of thallium atoms contain 122 neutrons and the remainder 124 neutrons.

(i) Deduce the nuclear symbol of the isotope of thallium containing 122 neutrons. Use section 7 of the data booklet. [1]



(ii) Calculate, to **two** decimal places, the relative atomic mass of thallium. [2]

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(b) Thallium (I) sulfate has the formula Tl_2SO_4.

(i) The compound contains both ionic and covalent bonds. State which particles are joined by covalent bonds and which are joined by ionic bonds. [2]

Covalent bond between: . . . . . and . . . . . .

Ionic bond between: . . . . . and . . . . . .

(ii) Contrast covalent and ionic bonds based on the valence electron interactions. [1]

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(This question continues on the following page)

(Question 2 continued)

(iii) State the enthalpy term that characterises the strength of the bonding between the ions in an ionic solid. [1]

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(iv) Write an equation for producing thallium(I) sulfate solution by reacting solid thallium(I) hydroxide with sulfuric acid. [2]

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(v) Calculate the volume of 2.00 mol dm^{-3} sulfuric acid required to react completely with 10.0 g of thallium(I) hydroxide. [3]

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(vi) Predict whether or not thallium(I) hydroxide is amphoteric, considering the position of thallium in the periodic table. [1]

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(This question continues on the following page)

(Question 2 continued)

(vii) Discuss how the relative reactivity of copper and thallium could be established using the metals and aqueous solutions of their sulfates. [2]

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(viii) Discuss the products at the electrodes when aqueous thallium (I) sulfate is electrolyzed.

Use standard reduction potential of $Tl^{+}(aq) + e^{-} \rightleftharpoons Tl(s) = -0.34\,V$ and section 19 of the data booklet. [2]

Anode (positive electrode): . . . . . .

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Cathode (negative electrode): . . . . . .

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(This question continues on the following page)

(Question 2 continued)

(c) Thallium has an atomic emission spectrum with a strong green line.

(i) State the feature of the atomic emission spectrum that may be used to find the ionization energy of the element. [1]

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(ii) Calculate the wavelength that corresponds to the ionization energy of thallium. Use sections 1, 2 and 9 of the data booklet. [3]

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(iii) Explain why, in terms of nuclear charge and the shielding of the valence electrons, the first ionization energy of thallium is lower than that of lead. [2]

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3. Phosgene (carbonyl dichloride, Cl_2CO) is an important industrial intermediate.

(a) Phosgene may be formed by the free-radical reaction between carbon monoxide, CO, and chlorine, Cl_2, which is initiated by UV light.

(i) Write an equation for the initiation reaction. [1]

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(ii) State the type of bond fission that is occurring. [1]

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(iii) Determine the enthalpy change for the reaction between carbon monoxide and chlorine from bond enthalpies. Use section 12 of the data booklet. [3]

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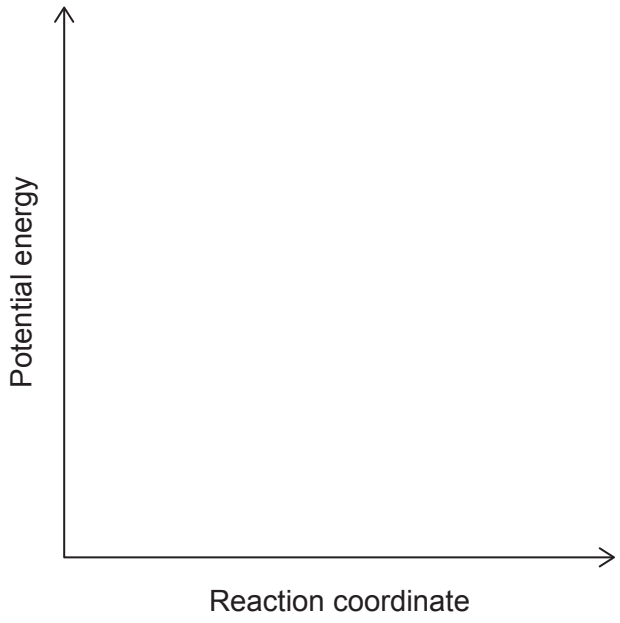
(Question 3 continued)

(iv) Sketch an energy profile for this reaction and label the "Reactants", "Products" and "ΔH". [2]



(v) Calculate the standard entropy change, $\Delta S^{\ominus}$, of the reaction between carbon monoxide and chlorine to form phosgene. Use section 13 of the data booklet and the following data:

Standard entropy $S^{\ominus}$, of chlorine $= 223\,\text{J}\,\text{mol}^{-1}\,\text{K}^{-1}$

Standard entropy $S^{\ominus}$, of phosgene $= 284\,\text{J}\,\text{mol}^{-1}\,\text{K}^{-1}$ [1]

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(This question continues on the following page)

(Question 3 continued)

(vi) Deduce whether the reaction would go to completion or reach equilibrium at 298 K. Use sections 1 and 2 of the data booklet along with your answers to (a)(iii) and (a)(v).

If you did not get an answer to (a)(iii) and/or (a)(v) use the following values, though these are not the correct answers: (a)(iii) = $-120\,kJ\,mol^{-1}$, (a)(v) = $-150\,J\,mol^{-1}\,K^{-1}$. [3]

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(b) Phosgene gradually decomposes in the environment according to the equation:

$$Cl_2CO\,(g) + H_2O\,(g) \rightarrow CO_2\,(g) + 2HCl\,(g)$$

(i) Suggest how the rate of this reaction could be followed at constant temperature. [1]

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(ii) Outline why some collisions between reactant molecules do not result in a reaction occurring. [2]

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(This question continues on the following page)

(Question 3 continued)

(iii) Write the rate equation for the reaction if it is first order with respect to each reactant. [1]

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(iv) If the reaction occurs in a dilute aqueous solution of phosgene it appears to be first order overall.

Outline why this is consistent with the answer to (b)(iii). [1]

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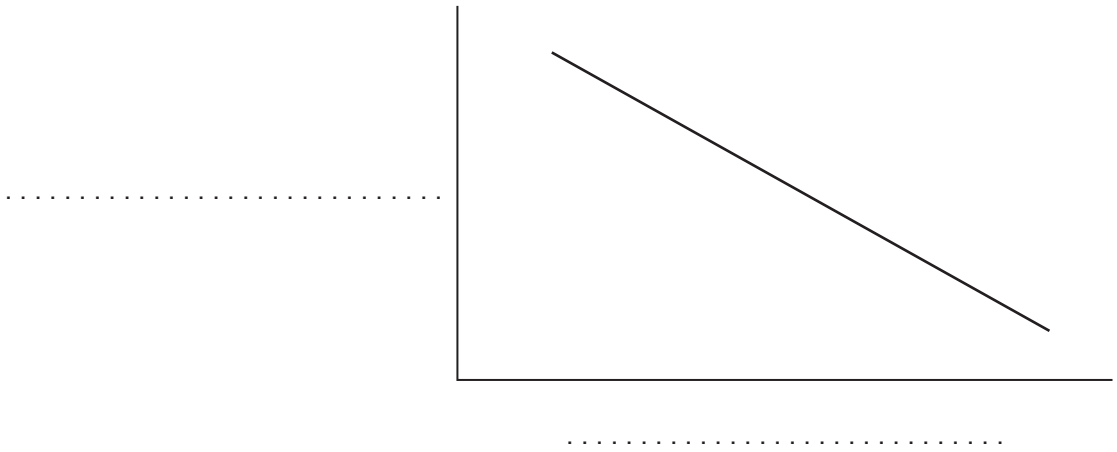
(v) The activation energy of this reaction was found by measuring the reaction rate over a range of absolute temperatures, *T*. The following graph was plotted:



State and label the axes of the graph. [1]

(vi) Calculate the gradient of the line on the graph in (b)(v) if the activation energy is $12\,kJ\,mol^{-1}$. Use sections 1 and 2 of the data booklet. [1]

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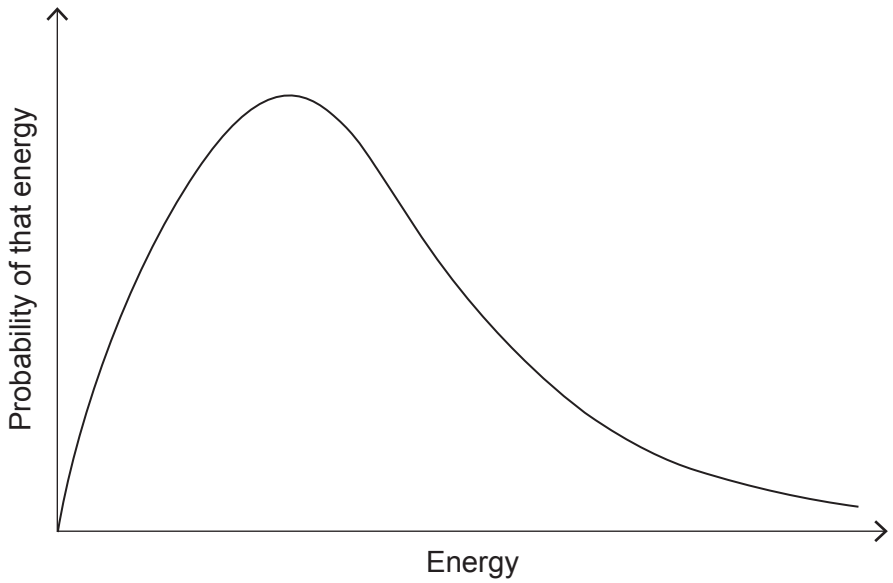
(Question 3 continued)

(vii) Sketch a Maxwell–Boltzmann energy distribution curve at a higher temperature than the one shown. [1]



(viii) Explain why the rate of reaction increases as the temperature is increased. Support your answer by annotating the diagram in (b)(vii). [2]

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(ix) Describe **two** observations which confirm that a solid, added to the reaction mixture, is acting as a catalyst. [2]

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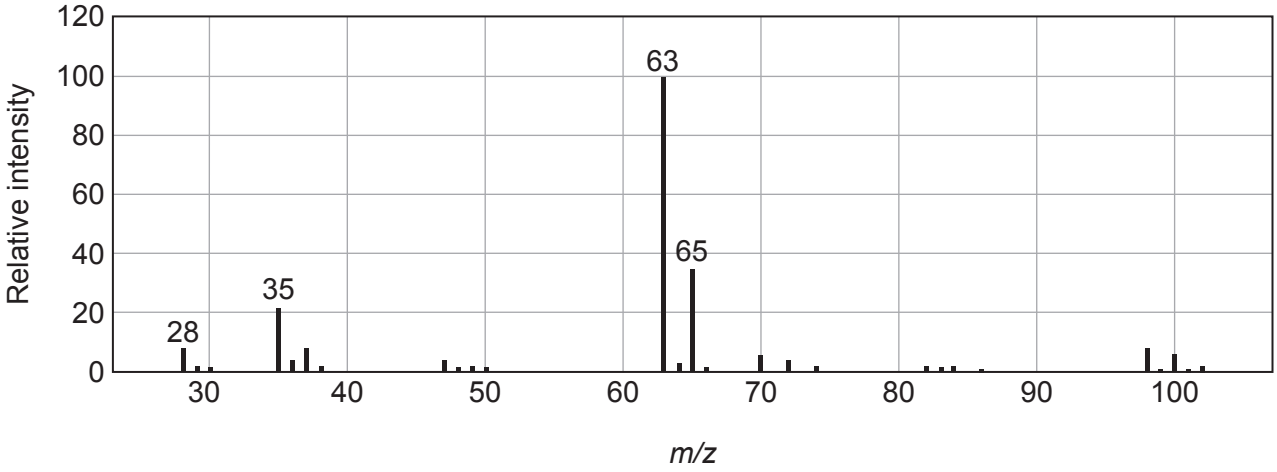
Answers written on this page
will not be marked.

(Question 3 continued)

(c) The mass spectrum of phosgene is shown.



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(i) Outline why there are peaks at *m/z* values less than that of the molecular ion. [1]

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(ii) Deduce the formula of the fragment that occurs at $m/z = 63$. [1]

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(iii) Predict the main features of IR and ^{1}H NMR spectra of phosgene. Use section 20 of the data booklet. [2]

IR: . . . . . .

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^{1}H NMR: . . . . . .

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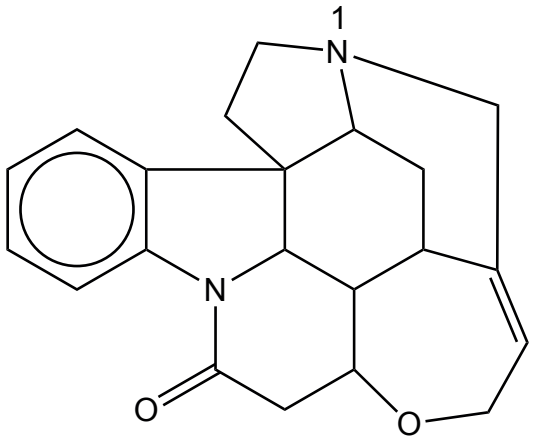
4. Strychnine, $C_{21}H_{22}N_2O_2$ (M_r = 334.4), is a white crystalline solid obtained from plants.

(a) The formula of strychnine is:



(i) State the name of the functional group containing the nitrogen atom labelled "1". [1]

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(ii) Outline how the functional group containing N_1 affects the pH when strychnine is dissolved in water. [1]

Direction of pH change: . . . . . .

Reason for change: . . . . . .

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(iii) Circle a functional group that would react with bromine in the dark on the diagram in (a). [1]

(iv) State the number of rings in strychnine's structure. [1]

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(This question continues on the following page)

(Question 4 continued)

(v) The strychnine structure contains *chiral* carbon atoms. Outline what is meant by this term. [1]

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(b) 48.73 g of strychnine was converted into its sulfate by the reaction:

$$2C_{21}H_{22}N_2O_2(aq) + H_2SO_4(aq) \rightarrow (C_{21}H_{23}N_2O_2)_2SO_4(aq)$$

Determine the percentage yield if 51.41 g of product was obtained. Use section 7 of the data booklet. [2]

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