

## COMPETENCE BASED DISCUSSION ITEMS

### Item one

Small-scale distilleries in Kabale produce local spirits or solvents from fermented sugarcane or cassava. When mixing ethanol with water or other components, the behaviour deviates from ideal due to intermolecular forces. This affects boiling points and separation efficiency during fractional distillation. Positive or negative deviations from Raoult's law can lead to azeotropes, making complete separation difficult. Processors need to understand these to optimise yield and purity while minimising energy costs.

### Tasks

- a) State Raoult's law for ideal solutions of two volatile liquids. Define ideal solution and explain why benzene + toluene mixture approximates ideal behaviour.
- b) Draw and label vapour pressure vs mole fraction diagrams for:
  - i) An ideal solution.
  - ii) A non-ideal solution showing positive deviation (e.g., ethanol + acetone).
  - iii) A non-ideal solution showing negative deviation (e.g., chloroform + acetone)..
- c) At 25°C, the vapour pressure of pure ethanol ( $P^{\circ}\text{ethanol}$ ) = 59 mmHg and pure water ( $P^{\circ}\text{water}$ ) = 24 mmHg. For an ideal solution with mole fraction of ethanol = 0.40, calculate the partial pressures and total vapour pressure using Raoult's law.
- d) If the actual total vapour pressure for this ethanol-water mixture is higher than predicted (positive deviation), explain the implication for boiling point and ease of distillation.
- e) For a non-ideal mixture showing negative deviation, predict qualitatively the effect on boiling point compared to ideal.
- f) Discuss how azeotrope formation e.g. 95.6% ethanol-water affects industrial alcohol production in Uganda and one method to break the azeotrope

g) Evaluate the importance of understanding deviations from Raoult's law for quality control in Uganda's growing beverage and solvent industries.

### **Scenario Item 2: Steam Distillation for Essential Oil Extraction from Local Plants**

Farmers and small processors in western Uganda (e.g., around Fort Portal or Kabarole) extract essential oils from citronella grass, eucalyptus leaves and lavender for use in cosmetics, soaps, perfumes, and medicinal products. These oils are immiscible with water and have high boiling points ( $>200^{\circ}\text{C}$ ), which would cause decomposition if distilled normally. Steam distillation allows extraction at lower temperatures ( $\sim 100^{\circ}\text{C}$ ) because the total vapour pressure of the immiscible mixture equals atmospheric pressure when the sum of individual vapour pressures reaches 760 mmHg. A processor collects distillate and needs to calculate composition or estimate molar mass from experimental data.

- a) Explain why steam distillation is suitable for separating immiscible liquids with high boiling points and low vapour pressures.
- b) Describe the process of steam distillation and one safety precaution relevant to school or small-scale setup.
- c) In a steam distillation of eucalyptus oil, the vapour pressure of water at the distillation temperature ( $98^{\circ}\text{C}$ ) is 707 mmHg and that of the essential oil is 53 mmHg. Calculate the ratio of moles of oil to moles of water in the distillate.
- d) If 15.0 g of essential oil is collected with 450 g of water in the distillate, calculate the approximate molar mass of the oil component.
- e) Discuss the advantages of steam distillation for essential oil production in Uganda. Link to economic benefits for farmers.
- f) Suggest a simple school practical to demonstrate steam distillation and how to separate the oil layer.
- g) Evaluate potential challenges and one improvement for small-scale Ugandan processors.

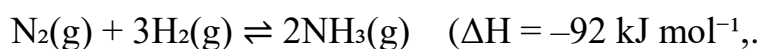
### **Scenario Item 3: Integration – Non-Ideal Behaviour in Azeotropes and Steam Distillation for Flavour Extraction**

In flavour and fragrance industries in Uganda, processors extract volatile compounds from plants e.g., vanilla and mint that may involve mixtures showing non-ideal behaviour. When separating miscible components, deviations from Raoult's law create distillation challenges (minimum or maximum boiling azeotropes). For heat-sensitive immiscible essential oils, steam distillation is preferred. A company analyses a mixture and plans to scale up production sustainably.

- Compare ideal and non-ideal solutions in terms of obedience to Raoult's law and draw a boiling point vs composition diagram for a maximum boiling azeotrope.
- Explain how steam distillation overcomes limitations of fractional distillation for immiscible systems.
- For an ethanol-water mixture (positive deviation leading to minimum boiling azeotrope), explain why pure ethanol cannot be obtained by simple distillation and how this relates to vapour pressure curves.
- In steam distillation of a plant oil, if  $P^\circ_{\text{water}} = 740 \text{ mmHg}$  and  $P^\circ_{\text{oil}} = 20 \text{ mmHg}$  at the distillation temperature, calculate the mass percentage of oil in the distillate assuming  $M_{r,\text{oil}} = 150$  and  $M_{r,\text{water}} = 18$ .
- Propose how knowledge of ideal/non-ideal behaviour and steam distillation can improve efficiency in Uganda's essential oils and agro-processing sector.

### **Scenario Item 4: Optimizing a Small-Scale Ammonia Plant for Ugandan Fertiliser Needs (Haber Process)**

A Ugandan entrepreneur plans a small-scale ammonia plant in Mbale to produce fertilisers locally, reducing imports for maize and coffee farmers. The Haber process reaction is:



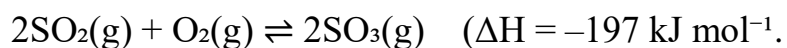
In a pilot reactor at  $450^\circ\text{C}$  and high pressure, equilibrium is established.

Data from one run (in a 10 dm<sup>3</sup> vessel): initial 2.0 mol N<sub>2</sub> and 6.0 mol H<sub>2</sub>; at equilibrium, 0.8 mol NH<sub>3</sub> is formed. Farmers need affordable NH<sub>3</sub> for urea production, but high energy costs and variable electricity supply are challenges. The plant must optimise yield while considering safety and environmental impact.

- a) Write the expression for K<sub>c</sub> for the Haber process.
- b) Using the data above, calculate the equilibrium concentrations of N<sub>2</sub>, H<sub>2</sub>, and NH<sub>3</sub>. Then determine the value of K<sub>c</sub> at 450°C.
- c) Using Le Chatelier's principle, predict and explain the effect on the position of equilibrium (yield of NH<sub>3</sub>) and on K<sub>c</sub> if:
  - i) Temperature is increased to 550°C.
  - ii) Pressure is increased (consider mole ratio).
  - iii) More N<sub>2</sub> is added (concentration change).
- d) A catalyst is used. Explain its effect on rate and equilibrium position/K<sub>c</sub>.
- e) Why does industry use a compromise temperature (~450°C) and high pressure (200–300 atm) rather than conditions for maximum yield?
- f) Discuss economic and environmental trade-offs for operating this plant in Uganda.
- g) Evaluate how understanding K<sub>c</sub> calculations helps chemical engineers optimise small-scale fertiliser production for food security in Uganda.

### **Item 5: Sulfuric Acid Production in a Proposed Ugandan Chemical Plant (Contact Process)**

A chemical company in Jinja considers setting up a Contact process plant to produce sulfuric acid for phosphate fertilisers and batteries. The key equilibrium step is:



In a converter at 450°C, equilibrium is reached with the following equilibrium concentrations:  $[\text{SO}_2] = 0.12 \text{ mol dm}^{-3}$ ,  $[\text{O}_2] = 0.08 \text{ mol dm}^{-3}$ ,  $[\text{SO}_3] = 1.5 \text{ mol dm}^{-3}$ .  $\text{SO}_3$  is then absorbed in concentrated  $\text{H}_2\text{SO}_4$ . Challenges include controlling emissions ( $\text{SO}_2$  causes acid rain) and energy costs in Uganda's variable power supply. High conversion is needed for economic viability

- a) Write the expression for  $K_c$  for the  $\text{SO}_2$  to  $\text{SO}_3$  reaction.
- b) Using the equilibrium concentrations above, calculate  $K_c$  at 450°C.
- c) If the temperature is raised to 550°C, predict qualitatively what happens to  $K_c$  and the yield of  $\text{SO}_3$ . Explain using Le Chatelier's principle.
- d) Predict and explain the effect on equilibrium position and  $K_c$  when:
  - i) Excess oxygen is added.
  - ii) Pressure is slightly increased.
  - iii) A  $\text{V}_2\text{O}_5$  catalyst is used.
- e) Discuss one environmental issue ( $\text{SO}_2$  emissions) and a control method suitable for Uganda.
- f) Evaluate the role of  $K_c$  calculations in designing efficient sulfuric acid plants to support Uganda's agriculture and manufacturing while minimising costs and pollution.

### **Scenario Item 6: Ester Production for Solvents and Flavours in Local Industry (Esterification Equilibrium)**

A small manufacturer in Kampala produces ethyl ethanoate (a solvent and flavouring agent) from local ethanol (from sugar cane) and ethanoic acid for use in cosmetics, paints, and pharmaceuticals. The reversible reaction is:



In a laboratory-scale batch (total volume 0.400 dm<sup>3</sup> after mixing), initial amounts are 0.350 mol  $\text{CH}_3\text{COOH}$  and 0.343 mol  $\text{C}_2\text{H}_5\text{OH}$ . After reaching equilibrium (catalyzed by conc.  $\text{H}_2\text{SO}_4$ ), titration shows 0.118 mol  $\text{CH}_3\text{COOH}$  remains. The

company wants to maximize ester yield cost-effectively for local markets, but equilibrium limits conversion. Removing water or using excess reactant could help.

- a) Write the expression for  $K_c$  for this homogeneous liquid equilibrium.
- b) Calculate the equilibrium amounts (in mol) and concentrations ( $\text{mol dm}^{-3}$ ) of all four species.
- c) Using Le Chatelier's principle, explain how to increase ester yield by:
  - i) Using excess ethanol.
  - ii) Removing water.
  - iii) Increasing temperature.
- d) Explain the role of the acid catalyst on rate versus equilibrium position/ $K_c$ .
- e) Discuss benefits of local ester production in Uganda.

### **Scenario Item 7: Antifreeze and Coolant Solutions for Vehicles in Uganda's Variable Climate**

Mechanics in Kampala and upcountry garages recommend adding ethylene glycol (a non-volatile solute,  $M_r = 62$ ) or similar compounds to radiator water in vehicles to prevent overheating in hot seasons and freezing in highland areas e.g Mt. Rwenzori regions during cold nights. The solution must raise the boiling point and lower the freezing point of water without corroding the engine. In a school lab, learners test the effect of adding different masses of a non-volatile solute to water.

#### **Given:**

$$K_f(\text{water}) = 1.86 \text{ } ^\circ\text{C kg mol}^{-1}$$

$$K_b(\text{water}) = 0.52 \text{ } ^\circ\text{C kg mol}^{-1}$$

Pure water freezes at  $0^\circ\text{C}$  and boils at  $100^\circ\text{C}$  (at standard pressure)

- a) Define colligative properties and explain why they depend only on the number of solute particles. List the four main colligative properties and describe how adding a non-volatile solute affects each in water.

- b) Calculate the freezing point depression and new freezing point when 62 g of ethylene glycol is dissolved in 1.0 kg of water.
- c) Calculate the boiling point elevation and new boiling point for the same solution
- e) Suggest a simple school experiment to demonstrate freezing point depression using naphthalene or stearic acid as solvent and a solute like naphthalene. Describe procedure, expected observations, and safety measures.
- f) Discuss real-life advantages and one disadvantage of using antifreeze solutions in Ugandan vehicles.

### **Scenario Item 8: Osmotic Pressure in Food Preservation and Juice Concentration in Uganda**

Food processors in Uganda preserve fruit juices e.g. pineapple and mango or make jams by adding high concentrations of sugar. This increases osmotic pressure, drawing water out of microbial cells and preventing spoilage. Farmers in Luwero supply fruits, but processors must calculate the right sugar concentration to achieve desired osmotic effects without making the product too sweet or affecting taste. Osmotic pressure also relates to plant water uptake in agriculture.

Given:

$$R = 0.083 \text{ dm}^3 \text{ atm mol}^{-1} \text{ K}^{-1} \text{ (or } 8.314 \text{ J mol}^{-1} \text{ K}^{-1}\text{)}$$

$$\text{Temperature} = 25^\circ\text{C}$$

A juice sample contains  $0.5 \text{ mol dm}^{-3}$  sucrose ( $M_r = 342$ )

- a) Explain osmotic pressure as a colligative property and describe the process of osmosis. Draw a simple diagram of osmosis across a semi-permeable membrane.
- b) Relate relative lowering of vapour pressure to boiling point elevation and osmotic pressure in solutions.
- c) Calculate the osmotic pressure ( $\pi$ ) of the juice solution at  $25^\circ\text{C}$ .
- d) If the concentration is doubled to  $1.0 \text{ mol dm}^{-3}$  sucrose, calculate the new osmotic pressure and predict the effect on microbial preservation.

- e) Determine the molar mass of an unknown non-volatile solute if 18 g dissolved in 0.5 dm<sup>3</sup> water gives an osmotic pressure of 3.95atm at 27°C.
- f) Discuss how high sugar concentration in jams uses osmotic pressure to preserve food in Ugandan households and small industries.

### **Scenario Item 9: Freezing Point Depression in Soil Solutions and Fertiliser Application**

In Ugandan agriculture, potato farming in Kabale highlands, fertilisers like urea or ammonium salts dissolve in soil water, affecting its colligative properties. High solute concentration can lower the freezing point of soil water in cold areas, preventing frost damage to roots, but excessive salts may cause osmotic stress to plants (reverse osmosis-like effect). Farmers need to understand these effects for optimal application rates.

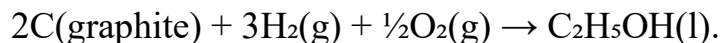
A lab test shows that a soil extract solution has a freezing point of  $-0.93^{\circ}\text{C}$ .

Given:  $K_f(\text{water}) = 1.86^{\circ}\text{C kg mol}^{-1}$ .

- a) Explain why adding solutes lowers vapour pressure, raises boiling point, and depresses freezing point of the solvent.
- b) Distinguish between ideal dilute solutions and real solutions
- c) Describe how learners could experimentally determine the effect of fertiliser concentration on freezing point using a simple setup e.g. with ice/salt mixtures or stearic acid).
- d) Link to plant physiology: Explain how high fertiliser concentrations can cause wilting via osmotic pressure differences between soil and plant cells.
- e) Evaluate the benefits and risks of using colligative properties knowledge for fertiliser management in Ugandan farming. Propose one recommendation for sustainable application.

## Scenario Item 10: Enthalpy of Formation of Ethanol for Biofuel Production in Uganda

Ethanol produced from cassava is promoted as a biofuel in Uganda to reduce reliance on charcoal and firewood, especially in rural areas of Masaka and Gulu. The formation reaction is:



This reaction cannot be measured directly in the laboratory. Instead, standard enthalpies of combustion are used. In a school experiment or industrial assessment, the following data (at 25°C) are available:

$$\Delta H_{\text{c}}^{\circ} \text{ of C}(\text{graphite}) = -394 \text{ kJ mol}^{-1}$$

$$\Delta H_{\text{c}}^{\circ} \text{ of H}_2(\text{g}) = -286 \text{ kJ mol}^{-1}$$

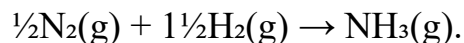
$$\Delta H_{\text{c}}^{\circ} \text{ of C}_2\text{H}_5\text{OH}(\text{l}) = -1367 \text{ kJ mol}^{-1}$$

Engineers need to determine the enthalpy of formation of ethanol to assess its energy efficiency compared to fossil fuels.

- Define standard enthalpy of formation ( $\Delta H_{\text{f}}^{\circ}$ ) and explain why the value for elements in their standard states (e.g C(graphite), H<sub>2</sub>(g), O<sub>2</sub>(g)) is zero.
- Draw a labelled energy cycle (Hess's Law diagram) showing the formation of ethanol via direct and indirect (combustion) routes.
- Using the combustion data above, construct the energy cycle and calculate  $\Delta H_{\text{f}}^{\circ}$  for C<sub>2</sub>H<sub>5</sub>OH(l).
- State the sign and magnitude of your calculated value and explain whether the formation of ethanol is exothermic or endothermic.
- Suggest two practical or environmental benefits of promoting ethanol production in Uganda, linking to enthalpy considerations and sustainability.

## Scenario Item 11: Enthalpy of Formation of Ammonia in Fertiliser Manufacture.

Ammonia (NH<sub>3</sub>) is a key intermediate for nitrogenous fertilisers (e.g., ammonium nitrate or urea) used by coffee and maize farmers in Mukono and Mbale districts. The formation reaction is:



Direct measurement is difficult, so Hess's Law with combustion or other data is applied. Given:

$\Delta H_{\text{f}}^{\circ}$  of NH<sub>3</sub>(g) needs calculation using combustion enthalpies or reaction data.

$\Delta H_{\text{c}}^{\circ}$  of NH<sub>3</sub>(g) = -383 kJ mol<sup>-1</sup> (to N<sub>2</sub> and H<sub>2</sub>O(l)).

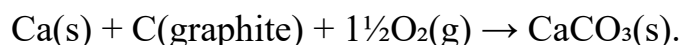
$\Delta H_{\text{f}}^{\circ}$  of H<sub>2</sub>O(l) = -286 kJ mol<sup>-1</sup>.

A local fertiliser plant must evaluate the energetics to optimise production and manage energy costs in Uganda's context of variable electricity sup

- Explain the difference between enthalpy of formation and enthalpy of combustion. Why is  $\Delta H_{\text{f}}^{\circ}$  for NH<sub>3</sub> important in thermochemical calculations for the Haber process?
- Sketch an energy cycle linking the formation of NH<sub>3</sub> to its combustion and the combustion of its elements.
- Using the provided combustion data (or standard values:  $\Delta H_{\text{c}}^{\circ}$  N<sub>2</sub> effectively 0 as it is not combustible in this context; adjust with H<sub>2</sub> and H<sub>2</sub>O), calculate  $\Delta H_{\text{f}}^{\circ}$  for NH<sub>3</sub>(g).
- Interpret the sign of  $\Delta H_{\text{f}}^{\circ}$  and link it to the exothermic nature of the Haber process overall.
- Discuss how a negative (exothermic)  $\Delta H_{\text{f}}^{\circ}$  influences the stability of ammonia and its suitability for fertiliser production
- Propose one way farmers or industries could use thermochemistry knowledge to improve fertiliser application and minimize environmental impact.

## Scenario Item 12: Enthalpy of Formation of Calcium Carbonate in Cement and Lime Industry

Cement and quicklime production in Uganda (e.g plants in Tororo and Hima) starts with limestone ( $\text{CaCO}_3$ ). The formation reaction is:



This is used to understand the energetics of decomposition (calcination:  $\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$ , endothermic). Given data:

$$\Delta H_{\text{f}}^{\circ} \text{ of CaO(s)} = -635 \text{ kJ mol}^{-1}$$

$$\Delta H_{\text{f}}^{\circ} \text{ of CO}_2(\text{g}) = -394 \text{ kJ mol}^{-1}$$

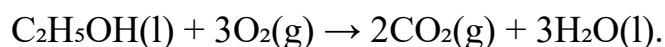
$\Delta H$  for the decomposition of  $\text{CaCO}_3(\text{s}) = +178 \text{ kJ mol}^{-1}$  (or use combustion-related cycles).

Engineers analyse these values to calculate energy requirements for high-temperature processes and assess sustainability.

- Define standard enthalpy of formation and state the conditions (298 K, 1 atm, standard states).
- Explain why Hess's Law is essential for determining  $\Delta H_{\text{f}}^{\circ}$  of compounds like  $\text{CaCO}_3$  that cannot be formed directly from elements.
- Construct an energy cycle using the given data to calculate  $\Delta H_{\text{f}}^{\circ}$  for  $\text{CaCO}_3(\text{s})$ .
- Compare the magnitude of  $\Delta H_{\text{f}}^{\circ}$  of  $\text{CaCO}_3$  with that of  $\text{CaO}$  and explain the stability of limestone.
- Evaluate the environmental challenges of energy-intensive cement production in Uganda and suggest how thermochemistry (enthalpy data) can support greener alternatives.
- Discuss one broader application of enthalpy of formation data in agriculture or construction materials in Uganda.

### Scenario Item 13: Energy Changes in Biofuel Production and Use in Ugandan Households (Enthalpy Changes, Calorimetry & Hess's Law)

Many rural households in Kanungu use ethanol or biodiesel produced from local crops like cassava as cleaner alternatives to charcoal and firewood. The production involves fermentation and combustion of ethanol:



A school laboratory experiment determines the enthalpy of combustion of ethanol using a simple spirit burner. In the experiment, 0.80 g of ethanol ( $M_r = 46$ ) is burned, heating 200 g of water in a calorimeter. The temperature of the water rises from 25.0°C to 38.5°C (specific heat capacity of water,  $c = 4.18 \text{ J g}^{-1} \text{ }^\circ\text{C}^{-1}$ ; assume no heat loss for calculation purposes.). Farmers and engineers need to compare the energy output of biofuels versus traditional fuels to promote sustainable energy and reduce deforestation.

- Draw and label an energy profile diagram for the combustion of ethanol, indicating whether it is exothermic or endothermic, the enthalpy change ( $\Delta H$ ), and the role of activation energy. Explain why activation energy is important in starting the reaction.
- Define standard enthalpy of combustion and explain its significance in thermochemical equations.
- Calculate the heat absorbed by the water ( $Q = mc\Delta T$ ) in kJ.
- Calculate the enthalpy of combustion of ethanol in  $\text{kJ mol}^{-1}$  (show steps, including moles of ethanol burned). Compare your value with the literature value (approx.  $-1367 \text{ kJ mol}^{-1}$ ) and suggest two reasons for any difference in a school experiment.
- Write the thermochemical equation for the combustion of ethanol, including the  $\Delta H$  value you calculated.
- Using Hess's Law and the following data, calculate the enthalpy change for the formation of ethanol from its elements (or another related cycle if data provided in class):

Enthalpy of combustion of carbon (graphite):  $-394 \text{ kJ mol}^{-1}$

Enthalpy of combustion of hydrogen:  $-286 \text{ kJ mol}^{-1}$

Enthalpy of combustion of ethanol: your calculated or given value.

g) Discuss one real-life application of enthalpy of combustion data in Uganda (e.g comparing energy efficiency of ethanol vs. charcoal for cooking and its environmental impact).

### Scenario Item 14: Lattice Energy and Born-Haber Cycle in Cement Manufacture (Born-Haber Cycles & Lattice Energy)

#### Problem Statement

Cement production in Uganda at a plant in Hima involves heating limestone ( $\text{CaCO}_3$ ) to produce quicklime ( $\text{CaO}$ ), which then reacts with other materials. The ionic compound  $\text{CaO}$  has a high lattice energy, contributing to its stability. Engineers study Born-Haber cycles to understand the energetics of forming ionic compounds like  $\text{CaO}$  or related salts used in construction. Data for a Born-Haber cycle for  $\text{CaO}$  might include: enthalpy of formation of  $\text{CaO}$ , atomization energies, ionisation energies, electron affinity, and lattice energy. This helps predict compound stability and feasibility of processes

a) Define lattice energy and explain its role in the stability of ionic compounds like  $\text{CaO}$ . State factors that affect the magnitude of lattice energy.

b) Draw a labelled Born-Haber cycle for the formation of  $\text{CaO}(s)$  from its elements, identifying all enthalpy changes involved (formation, atomization, ionisation, electron affinity, lattice energy).

c) Using provided, calculate the lattice energy of  $\text{CaO}$ .

$$\Delta H_f \text{ for CaO} = -635 \text{ kJ mol}^{-1}$$

$$\text{atomization of Ca} = +178 \text{ kJ mol}^{-1}$$

$$\text{Atomization enthalpy of oxygen} = +249 \text{ kJ mol}^{-1}$$

$$1^{\text{st}}\text{IE} = +590 \text{ kJ mol}^{-1}$$

**2nd IE = +1145 kJ mol<sup>-1</sup>**

**First electron affinity of oxygen = -141 kJ mol<sup>-1</sup>**

**Second electron affinity of oxygen = +798 kJ mol<sup>-1</sup>**

d) Predict qualitatively how the lattice energy of MgO compares to CaO and explain why.

e) Discuss how knowledge of lattice energy and Born-Haber cycles helps assess the feasibility and energy efficiency of producing cement or related materials in Uganda.

***ALUTA CONTINUA***