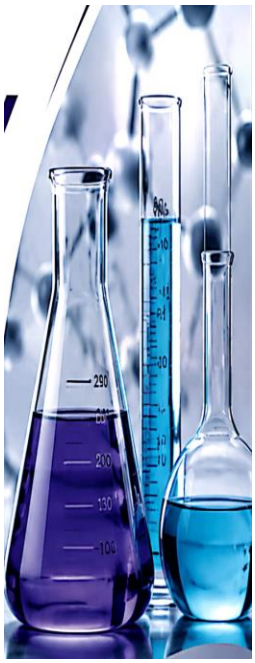
UACE
CHEMISTRY

CALVINE SCIENCE FOUNDATION

UGANDA ADVANCED CERTIFICATE OF EDUCATION

CHEMISTRY

CONTINUOUS ASSESSMENTS SERIES



Paper 1
(Theory)
2 Hours: 45 minutes

INSTRUCTIONS TO ITEM TAKERS

This paper consists of 10 compulsory questions.

All questions are equally weighted.

Responses to all items must be written in the answer booklet(s) provided.

Read thoroughly through every question before responding to it.

Candidate's Name: .....

Candidate's Number: .....

School: .....

DISCIPLINE • HARDWORK • INTEGRITY

Item 1

Medcare Formulations Ltd, a pharmaceutical company in Kampala, has expanded its women's health division to produce Aci-Jel Balance, a pH stabilizing vaginal medicine used in the management of vaginitis. The product relies on a controlled release system containing ethyl ethanoate, which hydrolyses in the body to generate small amounts of ethanoic acid essential for preventing harmful microbial growth.
During checkup, the chemist must verify the efficiency of ester production step, because the yield of ethyl ethanoate determines how well the final medicine will perform. The key step is the esterification reaction.

$$CH_3COOH_{(l)} + CH_3CH_2OH_{(l)} \leftrightharpoons CH_3COOCH_2CH_{3(l)} + H_2O_{(l)}\ \Delta H = \text{negative}$$

To check the product consistency, a batch test was conducted with 2.00 moles of ethanoic acid mixed with 10.00 moles of ethanol and sealed in a glass tube. The tube was kept in a water bath at 60^{o}C for several hours. After cooling, the tube was broken into cold water and the resulting mixture required 290cm^3 of 0.200M sodium hydroxide solution during titration to neutralize the unreacted ethanoic acid at equilibrium.
Chemists also prepared a 0.010M ethanoic acid solution with known dissociation constant $K_a = 1.8 \times 10^{-5}$. Because the final product must safely maintain pH inside the human body, the company designs a buffer system made from ethanoic acid and sodium ethanoate and must know how it works. The company manager and community is concerned about possible environmental impacts that may emerge from the industry. You have been contacted for help.

Task

As a learner of chemistry, guide the company on how to:

(a). Calculate the equilibrium constant for the esterification reaction and predict the extent of the reaction.
(b). Explain how both the amount of ethyl ethanoate produced, the position and rate of attainment of equilibrium would change if:
  (i). More ethanol is added to the resulting mixture.
  (ii). Water is removed during the reaction.
  (iii). Concentrated sulphuric acid is introduced.
  (iv). Sodium hydroxide solution contaminates the mixture.
  (v). Temperature was increased.
(c). Calculate the pH of the ethanoic acid solution above.
(d). Describe clearly how the buffer system in the medicine functions when it mixes with small acidic and basic body fluid amounts.

(e). Suggest the environmental impacts associated with the aqueous equilibria in this production and their mitigation measures.

Item 2

A technical report from Moroto Argo Chem industries (U) Ltd indicates that the company is optimizing its large scale ammonia production system, a key raw material used in fertilizers, cleaning agents and pH control formulations.

During Pilot testing, the industrial chemist introduced 1.00 moles of Nitrogen gas and 3.00 moles of Hydrogen gas into a 2.00dm^3 high pressure reactor. The mixture was compressed to 100atm and heated to 400^{o}C, allowing equilibrium to be established according to the reversible reaction.

$$N_{2\,(g)} + 3H_{2\,(g)} \leftrightharpoons NH_{3(g)}\ \Delta H = -92KJmol^{-1}$$

Gas analysis revealed that the equilibrium mixture contained 25% ammonia by volume, prompting management to evaluate how changes in operating variables such as pressure, temperature and catalysts might influence the position of equilibrium, the value of equilibrium constant and the rate of attainment of equilibrium in the reactor.

The company also manufactures buffered cleaning solutions by passing an equilibrium mixture through hydrochloric acid.

To test the stability of one formulation, the quality assurance unit prepared a 0.001M ammonia solution and needed to determine its pH as well as verify how the mixture behaves when ammonium chloride is added to create an ammonia to ammonium chloride buffer system. Because the buffer is used to maintain constant pH in enzyme based cleaning agents, the plant manager must be confident that the solution must suit its purpose. You have been invited to assist in analyzing the equilibrium data, pH and functioning of the buffer system.

Task

As a learner of chemistry, help the company to know:

(a). The equilibrium constant for the gaseous reaction K_p.

(b). How the equilibrium system is affected by:

(i). Passing the equilibrium mixture through hydrochloric acid.

(ii). Introducing a catalyst.

(iii). Increasing temperature.

(iv). Increasing pressure.

(c). Calculate the pH of the solution obtained. ($K_b = 1.8\times 10^{-5} moldm^{-3}$)

(d). How the buffer system works.

(e). Environmental impacts of the gaseous or aqueous equilibria and their mitigations.

Item 3

A report from Kabony Chemical Works (U) Ltd revealed that the company is improving its sulphuric acid production process an essential raw material used in fertilizers and lead acid batteries.

In one of the experiments, the company's chemist reacted 0.425 moles of sulphur dioxide with 0.294 moles of oxygen gas in a 1.60dm^3 sealed vessel. The gases were heated in the presence of a catalyst and equilibrium was established according to the reversible reaction.

$$2SO_{2(g)} + O_{2(g)} \leftrightharpoons 2SO_{3(g)} \quad \Delta H = -196KJmol^{-1}$$

After analysis, it was discovered that 52% of the oxygen gas had reacted and this made the management curious how operating conditions influence both the position of equilibrium and the rate of attainment of equilibrium in the process and environmental impacts of emissions.

Sulphur trioxide is always converted to sulphuric acid, the plant's key product for quality control, 25cm^3 of 0.05M sulphuric acid was diluted with 750cm^3 of pure water and the resulting solution was tested for acidity.

To confirm whether the product meets safety and concentration standards, the manager must know the pH of the diluted acid sample. The acid is used to produce lead (ii) sulphate used in battery plates.

The company's environmental unit reported that only 0.035gdm^{-3} of it dissolves in water at 17^{o}C and the manager sought to know its solubility product so as to predict the effects of waste discharge on nearby water sources. Concerned about these findings, the plant manager has invited you.

Task

As a learner of chemistry help the company to know:

(a). The equilibrium constant for the gaseous reaction K_c.

(b). Explain the effect on the position of equilibrium, the value of K_c and the rate of attainment of equilibrium by

(i). Adding more sulphur dioxide gas.

(ii). Introducing a catalyst.

(iii). Increasing temperature.

(iv). Increasing pressure.

(c). Calculate the pH of the solution obtained.

(d). Determine the solubility product of lead (ii) sulphate.

(e). Assess the environmental impacts of the gaseous or aqueous equilibria and their mitigations.

Item 4

Phosguard industries manufacture phosphorus derived reagents used in water treatment to remove heavy metal poisoning. Part of their continuous firing reactor line handles Phosphorus (V) chloride (PCl_5) as an intermediate.

The safety team performs gas phase equilibrium checks to ensure plant safety and downstream water treatment compatibility.

A gas phase equilibrium test was carried out by introducing 3.60 moles of phosphorus (V) chloride into a rigid vessel of volume 2.00dm^3 at a given temperature. Analysis showed 1% dissociation according to the following equation.

$$\boldsymbol{PCl_{5(g)} \leftrightharpoons PCl_{3(g)} + Cl_{2(g)}\ \Delta H = +124KJmol^{-1}}$$

Using this information, the equilibrium constant K_c can be determined.

In a follow up process optimization test, the company introduces an additional 0.050 moles of chlorine gas into the same system at the same temperature.

A treatment test was carried out where 0.208g of phosphorus (V) chloride was completely hydrolyzed in 1.00dm^3 of water producing hydrochloric acid (HCl). The acid produced supplies chloride ions (Cl^-) which are then used to react with lead (ii) ions (Pb^{2+}) in waste water to from a precipitate. Below are the equations

$$\boldsymbol{PCl_{5(g)} + 4H_2O_{(l)} \rightarrow H_3PO_{4(aq)} + 5HCl_{(aq)}}$$

$$\boldsymbol{Pb^{2+}{}_{(aq)} + 2Cl^-{}_{(aq)} \rightarrow PbCl_{2(s)}}$$

A sample of wastewater contains 0.020$moldm^{-3}$ of Pb^{2+} ions. You have been contacted for help.

Task

As a learner of chemistry, guide the company on how to:

(a). Calculate the equilibrium constant K_c and comment on the extent of the reaction.

(b). Determine the new equilibrium concentrations of all species during optimization and hence determine the direction in which the equilibrium shifts and explain your answer.

(c). Explain what would happen to the equilibrium position, the equilibrium constant (K_c) and the speed of attainment of equilibrium when the following changes are made.

(i). Increasing temperature.

(ii). Decreasing pressure.

(iii). Adding helium gas at constant volume.

(d). Advise the company on how to optimize operating conditions (temperature, pressure and concentration) in order to control equilibrium effectively, improve production efficiency and ensure safety in handling phosphorus (V) chloride.

(e). *Calculate the maximum number of moles of Pb^{2+} ions that can be precipitated by the chloride ions present. Comment whether chloride ions are sufficient to completely remove Pb^{2+} from the waste water.*

(f). *Suggest possible environmental impacts Phosguard industries should beware of and propose appropriate mitigation measures.*

Item 5

Nitrogen oxide plays a significant role in both industrial chemistry and environmental science. Nitrogen Monoxide (NO) is an important intermediate in the manufacture of nitric acid, which is widely used in explosives, fertilizers and dyes.

Understanding the behavior of nitrogen monoxide in the presence of oxygen is crucial as it forms Nitrogen Dioxide, a highly reactive gas.

Chemical engineers and their environmental chemists often study the equilibrium between these gases to optimize industrial processes while minimizing environmental impact.

In a controlled laboratory experiment, a chemical engineer decides to investigate the equilibrium characteristics of the reaction between nitrogen monoxide and oxygen.

$$\boldsymbol{2NO_{(g)} + O_{2(g)} \leftrightharpoons 2NO_{2\,(g)}}$$

To stimulate industrial conditions, she places 3 moles of nitrogen monoxide and 1.5 moles of oxygen into a sealed reaction vessel and heats it into 400^{o}C. After allowing sufficient time for the reaction to reach equilibrium. She measured the composition of the gases and finds that the vessel contains 0.5 moles of oxygen.

Curious about the effect of temperature on the reaction equilibrium, she increases the temperature of the vessel to 500^{o}C. At this elevated temperature, she observes that 25% of the initial nitrogen monoxide remains unreacted. She also considers practical industrial scenarios wondering how the introduction of an inert gas like helium might influence the equilibrium position and the value of the equilibrium constant.

Task

(a). *Using the data obtained at 400^{o}C, calculate the value of K_c at this temperature.*

(b). *With reference of the observations made at 500^{o}C calculate the equilibrium constant at this new temperature.*

(c). *From your calculations in (a) and (b) explain whether the reaction is exothermic or endothermic.*

(d). *Predict and explain the effect on K_c if an inert gas such as helium is added to the reaction mixture at constant volume.*

(e). *Assess some of the environmental impacts associated with the gaseous products and propose the probable mitigations.*

Item 6

Hydrogen Iodide (HI) is widely used in the chemical industry, particularly in the production of Iodine which is essential in pharmaceuticals, antiseptics, photography and as a catalyst in various chemical processes. Controlling the decomposition of Hydrogen Iodide is crucial for maximizing Iodine yield and ensuring safe industrial operations.

An industrial laboratory carried out an investigation to study the decomposition of hydrogen iodide gas at high temperatures. The decomposition reaction is represented as

$$\boldsymbol{2HI_{(g)} \leftrightharpoons H_{2(g)} + I_{2(g)}\ \Delta H = +113KJmol^{-1}}$$

In the experiment, 3.10g of hydrogen iodide was introduced into a clean, dry 600cm^3 glass bulb. The glass bulb was heated to 400^{o}C to initiate decomposition.
Overtime the reaction reached dynamic equilibrium where the concentrations of HI, H_2 and I_2 remained constant.
To accurately determine the amount of Iodine formed at equilibrium, the bulb was rapidly cooled to room temperature. The Iodine formed was dissolved in potassium iodide solution and the quantity of Iodine was measured by titration with 13.40cm^3 of 0.2M sodium thiosulphate solution. This type of analysis helps in monitoring industrial process, optimizing conditions and ensuring efficient use of raw materials.
Task

(a). Explain why the reaction mixture in the bulb was rapidly cooled after equilibrium was reached.

(b). Using the data provided, calculate the value of the equilibrium constant K_c at 400^{o}C.

(c). Predict and explain what would happen to the value of K_c if:

(i). The temperature was increased.

(ii). An inert gas is added at constant volume.

(iii). The volume of the bulb is increased from 600cm^3 to 1000cm^3.

Item 7

Uganda Manganese Chemicals Limited, a leading chemical manufacturing company situated in Jinja, specializes in producing high-purity manganese compounds that are widely used in industrial water treatment systems, battery production and as pigments in various chemical applications.
As part of the routine quality control and process optimization procedures, the plant's laboratory team conducted an experiment to monitor the equilibrium behavior of potassium manganate (vi) in water, which is a crucial step in ensuring the efficiency and safety of the production process.

In a controlled laboratory setup, the chemists carefully measured 0.5 moles of potassium manganate (vi) and mixed it with 3.6 grams of distilled water in a precisely calibrated 1dm^3 reaction vessel. The mixture was then left undisturbed to allow the chemical reaction to proceed to equilibrium. The disproportionation reaction under investigation is represented by the following chemical equation.

$$3MnO_4^{2-}{}_{(aq)} + 2H_2O_{(l)} \leftrightharpoons MnO_{2\,(s)} + 2MnO_4^{-}{}_{(aq)} + 4OH^-{}_{(aq)}$$

After equilibrium was established, careful laboratory analysis indicated that the reaction mixture contained 1.738 grams of manganese (iv) oxide. This data is critical for determining the equilibrium constant and evaluating the reaction's efficiency under the given conditions. The results are intended to guide adjustments in the industrial-scale process to maximize yield, ensure product quality and maintain safe operational standards.

Task

(a). Using the provided experimental data, calculate the value of the equilibrium constant K_c. Assume that the total volume of the reaction mixture remains at 1dm^3.

(b). Explain the importance of knowing the equilibrium constant in the context of industrial manganese compound production. Assess how this information helps the plant optimize reaction conditions and improve product yield.

(c). Explain the environmental impacts of the products of the industrial equilibria in the context and suggest the possible mitigations.

Item 8

The Kampala Industrial Chemicals Limited, situated in the industrial hub of Kampala, is a major manufacturer of sulphur trioxide (SO_3), a chemical compound that is extremely important in the production of sulphuric acid. Sulphuric acid is one of the most widely used industrial chemicals globally with applications in the manufacture of fertilizers, detergents, dyes and many other chemical products. The company has invested heavily in high-pressure, high temperature reactors to maximize the efficiency of sulphur trioxide production, while ensuring safety and minimizing environmental impact.

In one of the company's main production units, a precisely measured mixture of 3 moles of sulphur dioxide (SO_2) and 2 moles of oxygen (O_2) is introduced into a 1dm^3 high-pressure stainless steel reaction vessel. The vessel is equipped with temperature and pressure monitoring systems as well as safety release valves. The reactor is then heated to 450^{o}C and pressurized to 50 atmospheres in order to reach equilibrium as quickly as possible while maintaining safe operating conditions.

As the system reaches dynamic equilibrium, careful analysis of the gas composition indicates that the vessel contains 20% sulphur dioxide (SO_2) by mole fraction at equilibrium. This data is used by the company's chemical engineers to determine the

equilibrium constant and to optimize reaction conditions for maximum yield of sulphur trioxide.

The reaction taking place in the reactor is as follows

$$2SO_{2(g)} + O_{2(g)} \leftrightharpoons 2SO_{3(g)} \; \Delta H < 0$$

Industrial chemists must carefully balance temperature, pressure and reactant concentration to ensure the process is both efficient and economically viable as well as environmentally safe.

Task

(a). Using the data provided including the moles of reactants, the volume of the reaction vessel and the equilibrium composition, calculate the numerical value of the equilibrium constant K_p at 450^oC.

(b). In order to improve the production efficiency, the company is considering modifying the reaction conditions. State and explain how the concentration of sulphur trioxide at equilibrium would be affected under the following changes.

(i). If the pressure of the system is increased while the temperature remains constant.

(ii). If the temperature is increased while maintaining the same pressure.

(iii). If Xenon is added to the reaction vessel at constant pressure.

(c). Industrial chemists often face a trade-off between reaction rate and yield. Explain why the reaction is carried out at high pressure but moderate temperature.

(d). Suggest one practical industrial strategy that could be applied in the plant to further increase the yield of sulphur trioxide.

(e). Discuss briefly the environmental impacts and safety precautions that must be taken into account when handling sulphur trioxide. Sulphur dioxide and oxygen gas in the high-pressure chemical reactor.

Item 9

At MetroPharma Chemicals, one of Uganda's leading companies specializing in the production of antiseptic and disinfectant agents for hospitals and public health facilities, sulphur dioxide dichloride (SO_2Cl_2) is used as a critical intermediate in the synthesis of various sterilizing chemicals. Because SO_2Cl_2 is highly reactive and prone to dissociation at elevated temperatures, engineers at MetroPharma must carefully control reaction conditions to ensure safety, maximize product yield and maintain compliance with industrial chemical handling standards.

During routine quality control, a chemical engineer is tasked with analyzing a batch of SO_2Cl_2 stored in a specially designed high-pressure reaction chamber. This chamber is equipped with temperature and pressure sensors as well as a sampling port for gas analysis. The chamber is maintained at a high temperature of 375^oC and an overall pressure of $101325Nm^{-2}$. After sufficient time has elapsed to allow the reaction to reach

dynamic equilibrium, gas sampling reveals that approximately 84% of the SO_2Cl_2 molecules have dissociated into SO_2 and Cl_2 gases.

The engineer is aware that understanding the exact extent of dissociation is essential as deviations could lead to unsafe pressures or suboptimal concentrations of reactive intermediates. Additionally, the engineer must consider how different chemical interventions could affect the equilibrium constant for this reaction.

Task

(a). Calculate the equilibrium constant K_p for the dissociation of SO_2Cl_2 at 375^oC using the measured dissociation data.

(b). At constant temperature, discuss:

(i). How adding a catalyst to the system would affect the rate of reaching equilibrium, the position of equilibrium and the value of K_p.

(ii). How compressing the gas mixture by reducing the reactor volume would affect the position of equilibrium and whether it would alter the equilibrium constant K_p.

Item 10

EcoGrow Fertilizers Ltd, a leading agricultural company supplying urea-based fertilizers to farms across Uganda, relies heavily on careful control of chemical intermediates during production. One critical intermediate in urea production is ammonium carbamate (NH_4CONH_2) which decomposes spontaneously into ammonia (NH_3) and carbon dioxide (CO_2) gases. Improper control of this decomposition could lead to excess gas pressure in storage silos, posing safety hazards and also reduce the efficiency of subsequent synthesis.

During a routine safety inspection of a large storage silo containing solid ammonium carbamate, safety engineers use high-precision pressure sensors to monitor the internal gas pressure. The silo is maintained at 40^oC to mimic typical storage conditions. Analysis shows that the total pressure of gases in the silo is 0.36 atmospheres resulting from the decomposition of ammonium carbamate into gaseous ammonia and carbon dioxide. Engineers need to quantify the equilibrium behavior to ensure safe storage and maintain optimal conditions for later conversion into urea.

Task

(a). Using the measured total pressure, calculate the numerical value of K_p and clearly state its units.

(b). Discuss the effect on the value of K_p if:

(i). More solid ammonium carbamate is added to the silo.

(ii). The temperature is increased from 40^oC to 80^oC.

END