# THE SCHOOL FOR EXCELLENCE

# UNIT 4 CHEMISTRY 2009

# COMPLIMENTARY WRITTEN EXAMINATION 2 - SOLUTIONS

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# SECTION A - MULTIPLE CHOICE QUESTIONS

**QUESTION 1**      Answer is B

Catalysts are used to reduce the amount of energy required to have the reaction proceed at a reasonable rate.

**QUESTION 2**      Answer is C

Acid strength is determined by the $K_a$ value, and is not dependent on the concentration or volume of acid. Therefore, the acid with the lowest $K_a$ is the weakest species.
This is the acid in Bottle C.

**QUESTION 3**      Answer is A

**QUESTION 4**      Answer is D

**QUESTION 5**      Answer is D

Although equilibrium is established via a net forward reaction, the forward reaction rate is decreasing as the number of reactant particles is decreasing.

Note: Net forward means that the forward rate occurs more frequently than the back reaction rate. It does NOT mean that the forward reaction rate is increasing.

**QUESTION 6**      Answer is D

**QUESTION 7**      Answer is C

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**QUESTION 8**    Answer is C

$[H^+] = 10^{-7.60} = 2.511886 \times 10^{-8}$

In pure water, $[H^+] = [OH^-]$, therefore, $K_w = (2.511886 \times 10^{-8})^2 = 6.31 \times 10^{-16}$

**QUESTION 9**    Answer is C

$K_w = [H^+][OH^-] = 6.31 \times 10^{-16}$

$[H^+] = \dfrac{6.31 \times 10^{-16}}{[OH^-]} = \dfrac{6.31 \times 10^{-16}}{0.05} = 1.26 \times 10^{-14}$
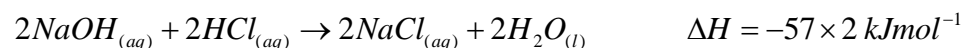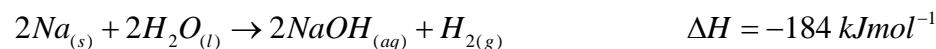
$pH = -\log_{10}(1.26 \times 10^{-14}) = 13.89$

**QUESTION 10**    Answer is C

**QUESTION 11**    Answer is B

**QUESTION 12**    Answer is A

**QUESTION 13**    Answer is B

**QUESTION 14**    Answer is A

$2Na_{(s)} + 2H_2O_{(l)} \rightarrow 2NaOH_{(aq)} + H_{2(g)}$ $\qquad \Delta H = -184 \, kJmol^{-1}$

$2NaOH_{(aq)} + 2HCl_{(aq)} \rightarrow 2NaCl_{(aq)} + 2H_2O_{(l)}$ $\qquad \Delta H = -57 \times 2 \, kJmol^{-1}$

Overall equation is $2Na_{(s)} + 2HCl_{(aq)} \rightarrow 2NaCl_{(aq)} + H_{2(g)}$

$\Delta H = -184 + (-57 \times 2) = -298 \, kJmol^{-1}$
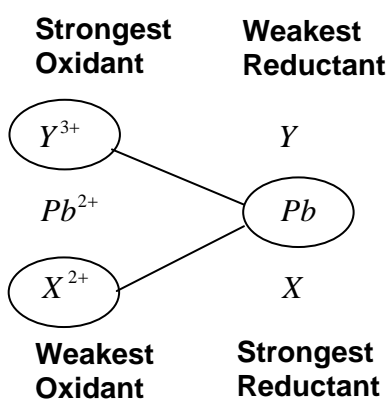
**QUESTION 15**    Answer is C

$m(C_2H_5OH) = dV = 0.789 \times 100 = 78.9 \, g$

$n(C_2H_5OH) = \dfrac{m}{M} = \dfrac{78.9}{46} = 1.72 \, mol$

1 mol $C_2H_5OH$ produces $1364 \, kJ$ (see data sheet) of energy, therefore, 1.72 mol produces $1.72 \times 1364 = 2346 \, kJ$

Calibration factor $= \dfrac{Energy(J)}{\Delta T} = \dfrac{2346}{10.4} = 225.58 = 226 \, kJ^oC^{-1}$

**QUESTION 16**     Answer is A

| **Strongest Oxidant** | **Weakest Reductant** |
|---|---|
| $Y^{3+}$ | $Y$ |
| $Pb^{2+}$ | $Pb$ |
| $X^{2+}$ | $X$ |
| **Weakest Oxidant** | **Strongest Reductant** |

**QUESTION 17**     Answer is A

A positive EMF does not guarantee that a reaction will occur spontaneously.
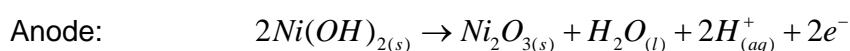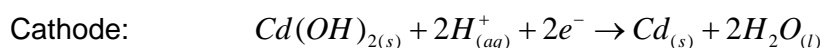
**QUESTION 18**     Answer is D

The distance between the electrodes affects the rate of electrolysis.
The greater the distance between the electrodes, the greater the resistance experienced from the electrolyte. This results in a weaker current passing through the electrolyte and hence electrolysis occurs at a slower rate.

**QUESTION 19**     Answer is B

The cathode reaction during discharge becomes the reaction at the anode (but reversed) during recharge.  The anode reaction during discharge becomes the reaction at the cathode (but reversed) during recharge.

**i.e. Recharging reactions:**

Cathode:        $Cd(OH)_{2(s)} + 2H^+_{(aq)} + 2e^- \rightarrow Cd_{(s)} + 2H_2O_{(l)}$

Anode:          $2Ni(OH)_{2(s)} \rightarrow Ni_2O_{3(s)} + H_2O_{(l)} + 2H^+_{(aq)} + 2e^-$

**QUESTION 20**     Answer is A

Water is a stronger oxidant than $Mg^{2+}$ and is preferentially reduced at the cathode.
Therefore, no magnesium will be produced.

$$n(e^-) = \frac{Q}{F} = \frac{5.79 \times 10^5}{96500} = 6.00 \; mol$$

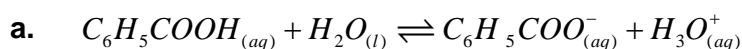$$n(Ni) = \frac{1}{2} \times n(e^-) = 3 \; mol \qquad m(Ni) = n \times M = 3 \times 58.7 = 176 \; g$$

$$n(Ag) = n(e^-) = 6 \; mol \qquad m(Ag) = n \times M = 6 \times 107.9 = 647 \; g$$

Ratio $Ni : Ag$ is $176 : 647$ i.e. $1 : 4$

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# SECTION B – SHORT ANSWER QUESTIONS

**QUESTION 1**

**a.** $C_6H_5COOH_{(aq)} + H_2O_{(l)} \rightleftharpoons C_6H_5COO^-_{(aq)} + H_3O^+_{(aq)}$

$$K_a = \frac{[C_6H_5COO^-_{(aq)}][H_3O^+_{(aq)}]}{[C_6H_5COOH_{(aq)}]} \ M \ \text{[1 mark]}$$

As $[C_6H_5COO^-_{(aq)}] = [H_3O^+_{(aq)}]$ at equilibrium and

$[C_6H_5COOH_{(aq)}]_{initial} \approx [C_6H_5COOH_{(aq)}]_{equilibrium} = 0.022 \ mol \ L^{-1}$

$\dfrac{[H_3O^+_{(aq)}]^2}{0.022} = 6.4 \times 10^{-5}$ [1 mark]  (Use data sheet to obtain the value of $K_a$ )

$[H_3O^+_{(aq)}] = 0.001187$

$pH = -\log_{10}[H_3O^+] = -\log_{10}(0.001187) = 2.9255 = 2.9$

**b.** Answer is D [1 mark]

When a strong acid is diluted by a factor of 10, the pH increases by 1.
In the case of a weak acid, a 1 in 10 dilution initially decreases the concentration of acid by 10 fold i.e. the pH increases by 1 unit. The position of equilibrium then shifts to the right as the result of the dilution and more $H_3O^+$ is produced. This has the effect of decreasing the pH, meaning that once equilibrium is re-established, the pH has increased by less than 1 unit. [1 mark]

**c.** To dissolve, the position of equilibrium must shift to the right. This reaction must also be associated with a decrease in temperature, as the forward reaction is favoured in response to an increase in temperature. [1 mark]

The forward reaction must therefore be endothermic. [1 mark]

**d.** As a benzoic acid solution is heated, a net forward reaction occurs, increasing the concentration of $C_6H_5COOH_{(aq)}$. [1 mark]

i.e.  $C_6H_5COOH_{(s)} \rightleftharpoons C_6H_5COOH_{(aq)}$
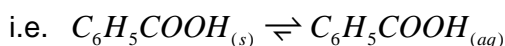
This drives the position of equilibrium in the reaction between the acid and water to the right, which results in an increase in $[H_3O^+]$. The pH therefore decreases. [1 mark]

$C_6H_5COOH_{(aq)} + H_2O_{(l)} \rightleftharpoons C_6H_5COO^-_{(aq)} + H_3O^+_{(aq)}$

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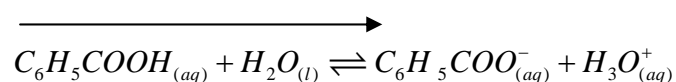
**QUESTION 2**

**a.** As the temperature increases, the yield of methanol decreases i.e. a net back reaction is occurring. [1 mark] This would occur in response to increasing the temperature of a system whose forward reaction is exothermic. [1 mark]

**b.** A catalyst will enable the system to reach the maximum yield in a shorter time frame – but it will not change the final yield. The curve must therefore start and end at the same concentrations, but the maximum concentration is reached sooner. [1 mark]

As catalysts increase reaction rates, the curve needs to be steeper. [1 mark]
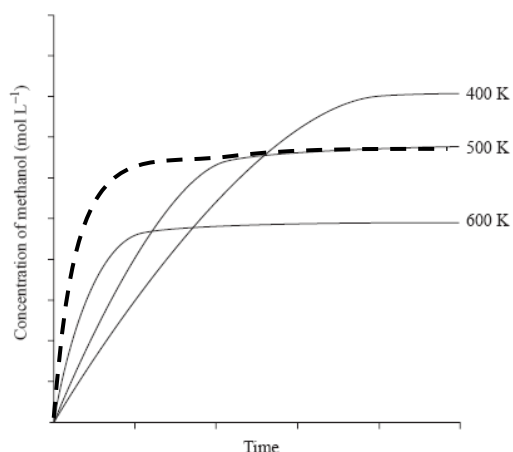


**c.** Mole ratios must be observed.

Equal amounts of both gases are added at constant volume i.e. concentration change is the same upon addition.

When the two reactants are added to the equilibrium mixture, a net forward reaction occurs. The reactant concentrations will gradually decrease but will never return to their previous values. As the reaction proceeds in a net forward reaction, the concentration of product gradually increases and then reaches a steady value.

**Note:** The concentration of $H_{2(g)}$ will change twice as much as the other gases (see mole ratios in balanced equation).

Concentration (M)
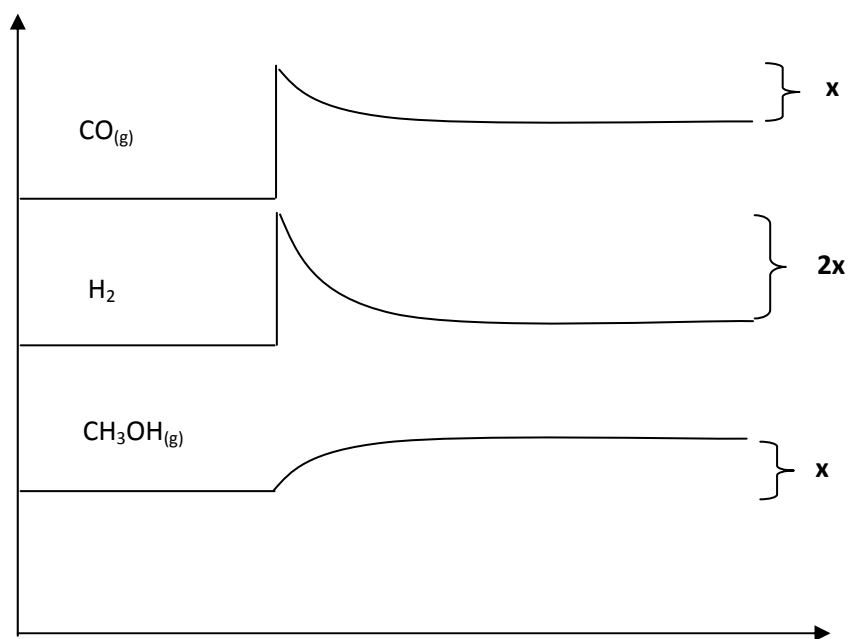


(Half mark for correctly showing the immediate concentration changes that occur in each species, half mark for correctly showing the changes in concentration (by using curves) and their final concentrations. Round down at the end of the question). [Total 3 marks]

**d.** $CO_{(g)} + 2H_{2(g)} \rightleftharpoons CH_3OH_{(g)}$
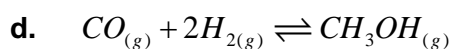
|  | $CO_{(g)}$ | $H_{2(g)}$ | $CH_3OH_{(g)}$ |
|---|---|---|---|
| **Initial Mole** | **0.40** | **0.50** | 0 |
| **Mole Ratio For Reaction** | 1 | 2 | 1 |
| **Mole Transferred** | $\frac{0.40}{2} = 0.20 \downarrow$ | $0.50 - 0.10 = 0.40 \downarrow$ | $0.20 \uparrow$ |
| **Mole at K** [1 mark] | $0.40 - 0.20 = 0.20$ | **n=cV=0.05×2=0.10** | $0 + 0.20 = 0.20$ |
| **Concentration at Equilibrium** | $C = \frac{0.20}{2} = 0.10M$ | $C = 0.05\,M$ | $C = \frac{0.20}{2} = 0.10M$ |

$$K = \frac{[CH_3OH_{(g)}]}{[CO_{(g)}][H_{2(g)}]^2}\,M^{-2} \quad \text{[1 mark]}$$

$$K = \frac{(0.10)}{(0.10)(0.05)^2}\,M^{-2} = 400\,M^{-2} = 4.0 \times 10^2\,M^{-2} \quad \text{[1 mark]}$$

**QUESTION 3**

**Experiment 1:** Opening the stopcock results in a decrease in the total pressure. The system compensates for the change by favouring the reaction that will increase the number of gaseous particles. A net back reaction occurs and hence the yield of product decreases. Note: Final concentration of $Cl_{2(g)}$ will be lower than in the initial equilibrium mixture as the increase in $Cl_{2(g)}$ production does not compensate for the drop in concentration that occurs when the volume of the vessel is increased.

**Experiment 2:** The addition of $Cl_{2(g)}$ results in an increase in the total pressure, but only changes the partial pressure of $Cl_{2(g)}$.

The system compensates for the change by favouring the reaction that will decrease the partial pressure of $Cl_{2(g)}$. A net forward reaction occurs and hence the yield of product increases. Note: Final concentration of $Cl_{2(g)}$ will be higher than in the initial equilibrium mixture.

**Experiment 3:** The addition of an inert gas results in an increase in the total pressure, but has no effect on the partial pressures of the reactants or the products. Therefore, there is no change in the position of equilibrium and hence the yield of product and $Cl_{2(g)}$ concentration do not change.

**a.** Experiment 2. [1 mark]

**b.** Experiment 2. [1 mark]

**c.** As temperature is held constant, the experiment which results in the production of higher concentrations of particles will result in the faster reaction rates.
i.e. Experiment 2 [1 mark]

As the concentration of reactants or products increases, the chances of reacting particles coming into contact increases. The probability of an effective collision increases, hence reaction rates increase. [1 mark]

**d.** $K = \dfrac{p(COCl_{2(g)})}{p(CO_{(g)})p(Cl_{2(g)})}\ atm^{-1}$    [1 mark – units must be correctly given]

**e.** As equal amounts of $CO_{(g)}$ and $Cl_{2(g)}$ are mixed and mole ratios for the reaction of the two species is 1:1, then $\left[CO_{(g)}\right]equilibrium = \left[Cl_{2(g)}\right]equilibrium$.
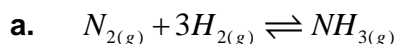
Hence $p(CO_{(g)}) = p(Cl_{2(g)}) = 2$ [1 mark]

$\dfrac{p(COCl_{2(g)})}{2 \times 2} = 0.66$

$p(COCl_{2(g)}) = 0.66 \times 4 = 2.64\ atm$   [1 mark]

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**QUESTION 4**

**Ammonia**

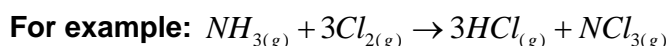**a.**   $N_{2(g)} + 3H_{2(g)} \rightleftharpoons NH_{3(g)}$
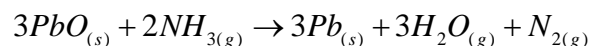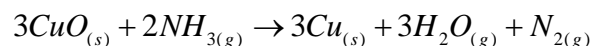
Reaction is endothermic.
[Both the equation and the nature must be correct to obtain the 1 mark]
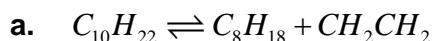
**b.**   By using higher temperatures.

**c.**   Reductants are reducing agents and undergo oxidation. Therefore, any equation which shows the oxidation number of nitrogen increasing will meet the requirements for a mark.

**For example:** $NH_{3(g)} + 3Cl_{2(g)} \rightarrow 3HCl_{(g)} + NCl_{3(g)}$

**For example:** Ammonia gas is a strong reducing agent and reduces heated metallic oxides to metals.

$3CuO_{(s)} + 2NH_{3(g)} \rightarrow 3Cu_{(s)} + 3H_2O_{(g)} + N_{2(g)}$
$3PbO_{(s)} + 2NH_{3(g)} \rightarrow 3Pb_{(s)} + 3H_2O_{(g)} + N_{2(g)}$

**Ethene**

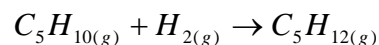**a.**   $C_{10}H_{22} \rightleftharpoons C_8H_{18} + CH_2CH_2$
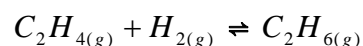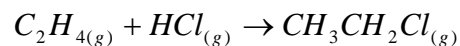Decane    Octane  Ethene

Reaction is endothermic.
[Both the equation and the nature must be correct to obtain the 1 mark]

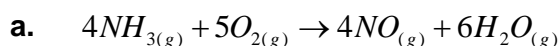**b.**   As the cracking process is endothermic, Le Chatelier's Principle suggests that high equilibrium yields of ethene will be favoured by higher temperatures and lower pressures (less than 1 atm).

**c.**   Oxidants are oxidising agents and undergo reduction. Therefore, any equation which shows the oxidation number of carbon decreasing will meet the requirements for a mark. Alternatively, in organic chemistry, reductions usually decrease the number of $C - O$ bonds or increase the number of $C - H$ bonds in the hydrocarbon.

**Examples include:**

$C_2H_{4(g)} + HCl_{(g)} \rightarrow CH_3CH_2Cl_{(g)}$
$C_2H_{4(g)} + H_{2(g)} \rightleftharpoons C_2H_{6(g)}$
$C_5H_{10(g)} + H_{2(g)} \rightarrow C_5H_{12(g)}$

## Nitric Acid

**a.**  $4NH_{3(g)} + 5O_{2(g)} \rightarrow 4NO_{(g)} + 6H_2O_{(g)}$
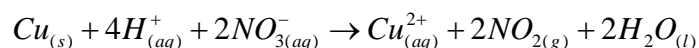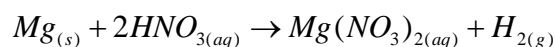
Exothermic
[Both the equation and the nature must be correct to obtain the 1 mark]

**b.**  The production of $NO$ is maximised by employing the following conditions:

- High temperatures $(820 - 930^o C)$
- High pressures (11 atm)

**c.**  Oxidants are oxidising agents and undergo reduction. Therefore, any equation which shows the oxidation number of nitrogen decreasing will meet the requirements for a mark.

$Mg_{(s)} + 2HNO_{3(aq)} \rightarrow Mg(NO_3)_{2(aq)} + H_{2(g)}$

$Cu_{(s)} + 4H^+_{(aq)} + 2NO^-_{3(aq)} \rightarrow Cu^{2+}_{(aq)} + 2NO_{2(g)} + 2H_2O_{(l)}$

## Sulfuric Acid

(a)  Sulfuric acid is mainly produced in large scale using the Contact process. Write the equation for the reaction that occurs in the converter during this process and state whether the forward reaction is endothermic or exothermic.
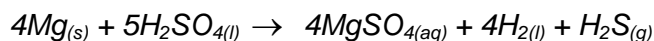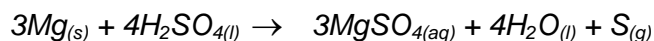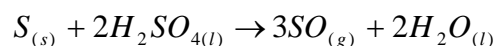
**a.**  $2SO_{2(g)} + O_{2(g)} \rightleftharpoons 2SO_{3(g)}$
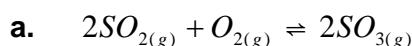
Exothermic
[Both the equation and the nature must be correct to obtain the 1 mark]

**b.**  Yields are maximised by using lower temperatures of approximately $450^o C$. Gases are cooled as they move across each catalyst bed so as to maximise the production of $SO_3$.

**c.**  Oxidants are oxidising agents and undergo reduction. Therefore, any equation which shows the oxidation number of sulfur decreasing will meet the requirements for a mark.

$S_{(s)} + 2H_2SO_{4(l)} \rightarrow 3SO_{(g)} + 2H_2O_{(l)}$

$Mg_{(s)} + 2H_2SO_{4(l)} \rightarrow MgSO_{4(aq)} + 2H_2O_{(l)} + SO_{2(g)}$

$3Mg_{(s)} + 4H_2SO_{4(l)} \rightarrow 3MgSO_{4(aq)} + 4H_2O_{(l)} + S_{(g)}$

$4Mg_{(s)} + 5H_2SO_{4(l)} \rightarrow 4MgSO_{4(aq)} + 4H_{2(l)} + H_2S_{(g)}$

**QUESTION 5**

**a.** Cathode: $Cu^{2+}_{(aq)} + 2e^- \rightarrow Cu_{(S)}$          [0.5 marks]

Anode: $Mg_{(S)} \rightarrow Mg^{2+}_{(aq)} + 2e^-$          [0.5 marks]

Overall: $Mg_{(S)} + Cu^{2+}_{(aq)} \rightarrow Mg^{2+}_{(aq)} + Cu_{(S)}$     [1 mark]        [Round down at end]

**b.** Negative     [1 mark]

**c.** Tube Y (as electrons flow from the anode of the galvanic cell (which is $Mg$) to the cathode of the electrolytic cell). [1 mark]

**d.** At high concentrations of $NaCl$, the predominant reaction at the anode will be $Cl^-_{(aq)} \rightarrow Cl_{2(g)} + 2e^-$. Therefore, $Cl_2$ gas will be observed. [1 mark]

**e.** Magnesium is the anode, therefore, it decreases in mass.

$$n(Mg)_{lost} = \frac{m}{M} = \frac{0.100}{24.3} = 0.0041152 \, mol$$

As $Mg_{(S)} \rightarrow Mg^{2+}_{(aq)} + 2e^-$ then $n(e^-)$ produced is $2 \times n(Mg) = 0.0082304 \, mol$ [1 mark]

This same number of mole of electrons travels to the cathode in the electrolytic cell and then to the anode of the electrolytic cell.
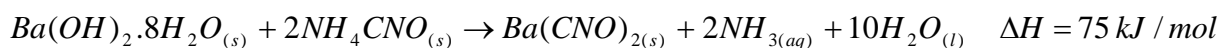
The reaction that occurs here is $2Cl^-_{(aq)} \rightarrow Cl_{2(g)} + 2e^-$.

$$n(Cl_{2(g)}) = \frac{1}{2} \times n(e^-) = \frac{1}{2} \times 0.0082304 = 0.0041152 \, mol \quad [1 \, mark]$$

**Volume of gas at STP:** $n = \dfrac{V}{22.4}$

$$\therefore V = 0.0041152 \times 22.4 = 0.0921804 \, L = 92.2 \, ml \quad [1 \, mark]$$

**QUESTION 6**

$$Ba(OH)_2.8H_2O_{(s)} + 2NH_4CNO_{(s)} \rightarrow Ba(CNO)_{2(s)} + 2NH_{3(aq)} + 10H_2O_{(l)} \quad \Delta H = 75\,kJ/mol$$

**a.** Determine which reactant is limiting.

$$n(Ba(OH)_2) = \frac{m}{M} = \frac{20}{315.3} = 0.06343\,mol \qquad \text{i.e. Limiting reactant} \quad \text{[1 mark]}$$

$$n(NH_4CNO) = \frac{m}{M} = \frac{20}{60} = 0.33333\,mol \qquad \text{i.e. In excess}$$

$$1\,mol\,Ba(OH)_2 \;\rightarrow\; 75\,kJ$$
$$0.06343\,mol\,Ba(OH)_2 \;\rightarrow\; x\,kJ$$

$$x = 4.75725 = 4.8\,kJ \quad \text{[1 mark]}$$

**b.** $E(J) = Calibration\ Factor \times \Delta T$

$$\Delta T = \frac{E(J)}{Calibration\ Factor} = \frac{4757.25}{200} = 23.786^{o}C \quad \text{[1 mark]}$$

Final Temperature = Initial Temperature – Temperature Change (as reaction is endothermic)

$$Temperature = 25.0 - 23.786 = 1.21375 = 1.21^{o}C \quad \text{[1 mark]}$$

**c.** (i) $\Delta H$ is the "difference" between the products and reactants. i.e. $x - z$

(ii) $x + y - z$

(iii) $z$

(iv) $x$ and $z$ (both answers required to obtain the full mark).

**QUESTION 7**

**a.** Onto the cathode [0.5 marks] as this is the electrode at which reduction takes place. [0.5 marks] [Round down].

**b.** (i) Number of Faradays = Number of mole of electrons transferred

$$n(e^-) = \frac{Q}{F} = \frac{It}{96,500} = \frac{1.55 \times 95 \times 60}{96,500} = 0.09155 \, mol$$

[1 mark for calculation of $It$]
[1 mark for correct answer]

(ii) $n(In) = \dfrac{m}{M} = \dfrac{3.50}{114.8} = 0.03049 \, mol$ [1 mark]

**c.** $In^{x+}_{(l)} + xe^- \rightarrow In_{(s)}$

$n(In) = \dfrac{1}{x} \times n(e^-)$ [1 mark]

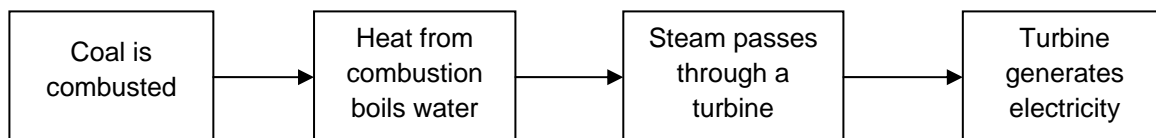$x = \dfrac{n(e^-)}{n(In)} = \dfrac{0.09155}{0.03049} = +3$ [1 mark]

**d.** Indium may be a weaker oxidant than water, and if this is the case, then it will not be reduced at the cathode as water is the stronger oxidant. [1 mark]

**e.** $E = VIt = QV = 1.55 \times 95 \times 60 \times 1.50 = 13252.5 \, J = 1.33 \times 10^1 \, kJ$ [1 mark]

# BONUS QUESTION

**QUESTION 8**

**a.**    (Half a mark per correct energy transformation. Round down)

| Coal is combusted | → | Heat from combustion boils water | → | Steam passes through a turbine | → | Turbine generates electricity |
|---|---|---|---|---|---|---|

| Chemical to Thermal energy | Thermal to Kinetic energy | Kinetic to Mechanical energy | Mechanical to Electrical energy |
|---|---|---|---|

**b.**    In $10.0\,kg$ of brown coal there are $7000\,g$ of carbon and $3000\,g$ of water.

$$n(C) = \frac{m}{M} = \frac{7000}{12} = 583.3\,mol$$

The combustion of 1 mole of carbon produces $394\,kJ$ of energy (see data sheet), therefore, the combustion of $583.3\,mol$ releases $583.3 \times 394 = 229,820\,kJ$ [1 mark].

However, some of this energy is used to evaporate the water that is present.

$$n(H_2O) = \frac{m}{M} = \frac{3000}{18} = 166.7\,mol$$

The energy required to evaporate 1 mole of water is $44.0\,kJ$. Therefore, $166.7\,mol$ would require $166.7 \times 44 = 7335\,kJ$ [1 mark].

The net energy released upon the combustion of $10.0\,kg$ of brown coal is
$229,820 - 7335 = 222885\,kJ = 2.22 \times 10^5\,kJ$ [1 mark].

**c.**    As coal is not a pure substance and hence the mole reacting cannot be accurately determined from its mass. [1 mark]

**d.**    Hydrogen [1 mark]
Energy per gram: $143\,kJg^{-1}$ [1 mark]
(Refer to formula sheet for molar heats of combustion)

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