3.2.1 Energetics

Hess's Law

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183 minutes

181 marks

Q1. (a) Define the term *standard molar enthalpy of formation*, $\Delta H_f^{\ominus}$.

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(3)

(b) State Hess's law.

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(1)

(c) Propanone, CH_3COCH_3, burns in oxygen as shown by the equation

$$CH_3COCH_3(l) + 4\,O_2(g) \rightarrow 3H_2O(l) + 3CO_2(g)$$

Use the data given below to calculate the standard enthalpy of combustion of propanone.

	$CO_2(g)$	$H_2O(l)$	$CH_3COCH_3(l)$
$\Delta H_f^{\ominus}$/kJ mol^{-1}	–394	–286	–248

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(3)
(Total 7 marks)

Q2. (a) What is the meaning of the term *enthalpy change*?

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(2)

(b) (i) Define the term *standard enthalpy of formation* of a compound.

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(ii) Write an equation, including state symbols, for the formation from its elements of solid sodium sulphate, Na_2SO_4

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(5)

(c) State Hess's Law.

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(1)

(d) Some standard enthalpy changes are difficult to measure directly but can be determined from standard enthalpies of combustion.
Maleic acid, $C_4H_4O_4$, reacts with oxygen to form carbon dioxide and water as shown by the following equation.

$$C_4H_4O_4(s) + 3O_2(g) \rightarrow 4CO_2(g) + 2H_2O(l)$$

Use the standard enthalpy of combustion data given below to calculate a value for the standard enthalpy change for the following reaction.

$4C(s) + 2H_2(g) + 2O_2(g) \rightarrow C_4H_4O_4(s)$

	$C_4H_4O_4(s)$	C(s)	$H_2(g)$
ΔH_c^{θ} / kJ mol^{-1}	–1356	–393.5	–285.8

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(3)
(Total 11 marks)

Q3. The table below contains some mean bond enthalpy data.

Bond	H—H	C—C	C=C	N≡N	N—H
Mean bond enthalpy / kJ mol^{-1}	436	348	612	944	388

(a) Explain the term *mean bond enthalpy.*

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(2)

(b) (i) Write an equation for the formation of one mole of ammonia, NH_3, from its elements.

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(ii) Use data from the table above to calculate a value for the enthalpy of formation of ammonia.

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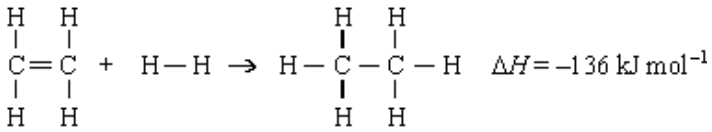
(c) Use the following equation and data from the table above to calculate a value for the C–H bond enthalpy in ethane.



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(3)
(Total 9 marks)

Q4. The table below contains some standard enthalpy of formation data.

Substance	C(s)	$N_2(g)$	$H_2O(g)$	$CO_2(g)$	$NH_4NO_3(s)$
$\Delta H_f^{\ominus}$ / kJ mol^{-1}	0	0	–242	–394	–365

(a) Why are the values of the standard enthalpy of formation for carbon and nitrogen zero?

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(1)

(b) State Hess's Law.

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(2)

(c) Use $\Delta H_f^{\ominus}$ data from the table to calculate a value for the enthalpy change for the following reaction.

$$NH_4NO_3(s) + \frac{1}{2}C(s) \rightarrow N_2(g) + 2H_2O(g) + \frac{1}{2}CO_2(g)$$

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(3)

(Total 6 marks)

Q5. (a) Write an equation for the complete combustion of propanone, C_3H_6O, to form carbon dioxide and water.

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(1)

(b) In a laboratory experiment, 1.45 g of propanone were burned completely in oxygen. The heat from this combustion was used to raise the temperature of 100 g of water from 293.1 K to 351.2 K.

(i) Calculate the number of moles of propanone in the 1.45 g.

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(ii) Calculate the heat energy required to raise the temperature of 100 g of water from 293.1 K to 351.2 K.

(The specific heat capacity of water is 4.18 J K^{-1} g^{-1})

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(iii) Hence, calculate a value, in kJ mol^{-1}, for the enthalpy of combustion of propanone.

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(5)

(c) In a similar experiment, the enthalpy of combustion of butanone, C_4H_8O, was found to be –1290 kJ mol^{-1}. A data book value for the same reaction is $\Delta H_c^{\ominus}$ = –2430 kJ mol^{-1}.

(i) Suggest one reason why the experimental value is very different from the data book value.

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(ii) This data book value of $\Delta H_c^{\ominus}$ for butanone (–2430 kJ mol^{-1}) refers to the formation of carbon dioxide gas and water in the gaseous state. How would this value differ if it referred to the formation of water in the liquid state? Explain your answer.

Difference .....

Explanation .....

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(3)

(d) Calculate a value for the standard enthalpy of formation for liquid ethanethiol, C_2H_5SH. Use the equation given below and enthalpy of combustion data from the following table.

Substance	$C_2H_5SH(l)$	C(s)	$H_2(g)$	S(s)
$\Delta H_c^{\ominus}$ / kJ mol^{-1}	–1170	–394	–286	–297

$2C(s) + 3H_2(g) + S(s) \rightarrow C_2H_5SH(l)$

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(3)
(Total 12 marks)

Q6. (a) Define the term *standard enthalpy of formation*.

(3)

(b) State Hess's Law and use it, together with the data given in the table below, to calculate the standard enthalpy change for the following reaction.

$MgO(s) + 2HCl(g) \rightarrow MgCl_2(s) + H_2O(l)$

	MgO	HCl(g)	$MgCl_2$	H_2O
$\Delta H_f^{\ominus}$/kJ mol^{-1}	–602	–92	–642	–286

(4)

(c) In an experiment, an excess of solid magnesium oxide was added to 50 cm^3 of 3.0 mol dm^{-3} hydrochloric acid. The initial temperature of the solution was 21 °C. After reaction, the temperature had risen to 53 °C. (The specific heat capacity of water is 4.2 J K^{-1} g^{-1})

Use this information to calculate the enthalpy change for the reaction of one mole of magnesium oxide with hydrochloric acid. For your calculation you should assume that all the heat from the reaction is used to raise the temperature of 50 g of water.

(8)

(Total 15 marks)

Q7. (a) The table below contains some mean bond enthalpy data.

Bond	H–O	O–O	O=O
Mean bond enthalpy/kJ mol^{-1}	463	146	496

The bonding in hydrogen peroxide, H_2O_2, can be represented by H–O–O–H. Use these data to calculate the enthalpy change for the following reaction.

$$H_2O_2(g) \rightarrow H_2O_2(g) + \tfrac{1}{2} O_2(g)$$

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(3)

(b) The standard enthalpy of formation, $\Delta H_f^{\ominus}$ for methane, is –74.9 kJ mol^{-1}. Write an equation, including state symbols, for the reaction to which this enthalpy change applies.

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(2)

(c) The enthalpy changes for the formation of atomic hydrogen and atomic carbon from their respective elements in their standard states are as follows.

$\frac{1}{2}H_2(g) \rightarrow H(g)$ $\quad \Delta H^{\ominus} = +218$ kJ mol^{-1}

$C(s) \rightarrow C(g)$ $\quad \Delta H^{\ominus} = +715$ kJ mol^{-1}

(i) By reference to its structure, suggest why a large amount of heat energy is required to produce free carbon atoms from solid carbon.

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(ii) Parts (b) and (c) give enthalpy data for the formation of $CH_4(g)$, H(g) and C(g).

Use these data and Hess's Law to calculate the value of the enthalpy change for the following reaction.

$CH_4(g) \rightarrow C(g) + 4H(g)$

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(iii) Use your answer from part (c)(ii) to calculate a value for the mean bond enthalpy of a C–H bond in methane.

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(5)

(Total 10 marks)

Q8. Methanol, CH_3OH, is a convenient liquid fuel.

(a) An experiment was conducted to determine the enthalpy of combustion of liquid methanol. The energy obtained from burning 2.12 g of methanol was used to heat 150 g of water. The temperature of the water rose from 298 K to 362 K. (The specific heat capacity of water is 4.18 J K^{-1} g^{-1})

(i) Define the term *standard enthalpy of combustion*.

(ii) Use the data above to calculate a value for the enthalpy of combustion of one mole of liquid methanol.

(7)

(b) Methanol can be synthesised from methane and steam by a process that occurs in two stages.

Stage 1 $CH_4(g) + H_2O(g) \rightleftharpoons 3H_2(g) + CO(g)$ $\Delta H^{\ominus} = +206 \text{ kJ mol}^{-1}$

Stage 2 $CO(g) + 2H_2(g) \rightleftharpoons CH_3OH(g)$ $\Delta H^{\ominus} = -91 \text{ kJ mol}^{-1}$

(i) Explain why, in *Stage 1*, a higher yield of hydrogen and carbon monoxide is **not** obtained if the pressure is increased.

(ii) *Stage 2* is carried out at a compromise temperature of 500K. By considering what would happen at higher and lower temperatures, explain why 500 K is considered to be a compromise for *Stage 2*.

(5)

(c) The standard enthalpies of combustion of carbon monoxide and of hydrogen are -283 kJ mol^{-1} and -286 kJ mol^{-1}, respectively. Use these data and the enthalpy change for *Stage 2* to calculate a value for the standard enthalpy of combustion of gaseous methanol.

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(Total 15 marks)

Q9. (a) Explain the meaning of the terms *mean bond enthalpy* and *standard enthalpy of formation*.

Mean bond enthalpy .....

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Standard enthalpy of formation .....

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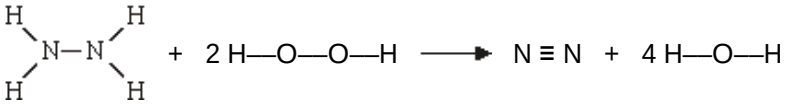
(5)

(b) Some mean bond enthalpies are given below.

Bond	N–H	N–N	N≡N	H–O	O–O
Mean bond enthalpy/kJ mol^{-1}	388	163	944	463	146

Use these data to calculate the enthalpy change for the following gas-phase reaction between hydrazine, N_2H_4, and hydrogen peroxide, H_2O_2



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(3)

(c) Some standard enthalpies of formation are given below.

	$N_2H_4(g)$	$H_2O_2(g)$	$H_2O(g)$
$\Delta H_f^{\ominus}$ /kJ mol^{-1}	+75	–133	–242

These data can be used to calculate the enthalpy change for the reaction in part (b).

$$N_2H_4(g) + 2H_2O_2(g) \rightarrow N_2(g) + 4H_2O(g)$$

(i) State the value of $\Delta H_f^{\ominus}$ for $N_2(g)$.

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(ii) Use the $\Delta H_f^{\ominus}$ values from the table to calculate the enthalpy change for this reaction.

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(4)

(d) Explain why the value obtained in part (b) is different from that obtained in part (c)(ii).

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(1)
(Total 13 marks)

Q10. (a) Define the term *standard enthalpy of combustion*, $\Delta H_c^{\ominus}$

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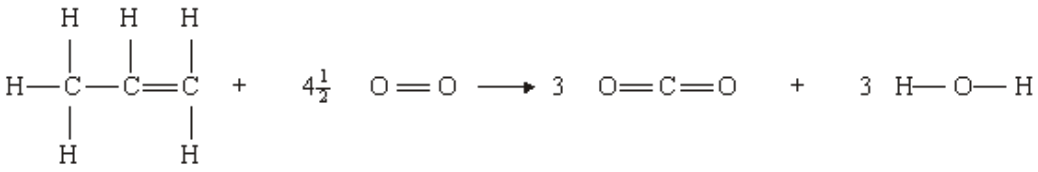
(3)

(b) Use the mean bond enthalpy data from the table and the equation given below to calculate a value for the standard enthalpy of combustion of propene. All substances are in the gaseous state.

Bond	C == C	C—C	C—H	O == O	O == C	O—H
Mean bond enthalpy/ kJ mol^{-1}	612	348	412	496	743	463



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(3)

(c) State why the standard enthalpy of formation, $\Delta H_f^{\ominus}$, of oxygen is zero.

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(1)

(d) Use the data from the table below to calculate a more accurate value for the standard enthalpy of combustion of propene.

Compound	$C_3H_6(g)$	$CO_2(g)$	$H_2O(g)$
Standard enthalpy of formation, $\Delta H_f^{\ominus}$/ kJ mol^{-1}	+20	–394	–242

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(3)

(e) Explain why your answer to part (b) is a less accurate value than your answer to part (d).

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(2)

(Total 12 marks)

Q11. (a) Define the term *standard enthalpy of formation*, $\Delta H_f^{\ominus}$

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(3)

(b) Use the data in the table to calculate the standard enthalpy of formation of liquid methylbenzene, C_7H_8

Substance	C(s)	$H_2(g)$	$C_7H_8(l)$
Standard enthalpy of combustion, $\Delta H_c^\ominus$ /kJ mol^{-1}	–394	–286	–3909

$7C(s) + 4H_2(g) \rightarrow C_7H_8(l)$

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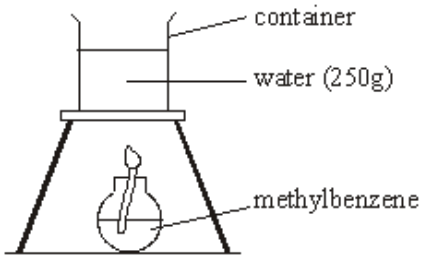
(3)

(c) An experiment was carried out to determine a value for the enthalpy of combustion of liquid methylbenzene using the apparatus shown in the diagram.



Burning 2.5 g of methylbenzene caused the temperature of 250 g of water to rise by 60°C. Use this information to calculate a value for the enthalpy of combustion of methylbenzene, C_7H_8

(The specific heat capacity of water is 4.18 J K^{-1} g^{-1}. Ignore the heat capacity of the container.)

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(4)

(d) A 25.0 cm^3 sample of 2.00 mol dm^{-3} hydrochloric acid was mixed with 50.0 cm^3 of a 1.00 mol dm^{-3} solution of sodium hydroxide. Both solutions were initially at 18.0 °C.

After mixing, the temperature of the final solution was 26.5°C.

Use this information to calculate a value for the standard enthalpy change for the following reaction.

$HCl(aq) + NaOH(aq) \rightarrow NaCl(aq) + H_2O(l)$

In your calculation, assume that the density of the final solution is 1.00 g cm^{-3} and that its specific heat capacity is the same as that of water. (Ignore the heat capacity of the container.)

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(4)

(e) Give **one** reason why your answer to part (d) has a much smaller experimental error than your answer to part (c).

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(1)

(Total 15 marks)

Q12. Hess's Law is used to calculate the enthalpy change in reactions for which it is difficult to determine a value experimentally.

(a) State the meaning of the term *enthalpy change*.

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(1)

(b) State Hess's Law.

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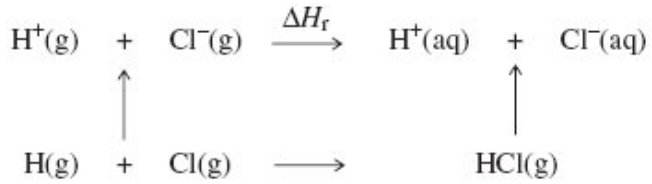
(1)

(c) Consider the following table of data and the scheme of reactions.

Reaction	Enthalpy change / kJ mol^{-1}
$HCl(g) \rightarrow H^+(aq) + Cl^-(aq)$	–75
$H(g) + Cl(g) \rightarrow HCl(g)$	–432
$H(g) + Cl(g) \rightarrow H^+(g) + Cl^-(g)$	+963



Use the data in the table, the scheme of reactions and Hess's Law to calculate a value for ΔH_r

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(3)
(Total 5 marks)

Q13. This question is about the extraction of titanium from titanium(IV) oxide by a two-stage process.
The first stage in the process produces titanium(IV) chloride. In the second stage, titanium(IV) chloride is converted into titanium.
The enthalpy change for the second stage can be determined using Hess's Law.

(a) Give **one** reason why titanium is **not** extracted directly from titanium(IV) oxide using carbon.

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(1)

(b) Give the meaning of the term *enthalpy change*.

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(1)

(c) State Hess's Law.

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(1)

(d) Define the term *standard enthalpy of formation*.

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(3)

(e) The following standard enthalpy of formation data refer to the second stage in the extraction of titanium.

	$TiCl_4(g)$	Na(l)	NaCl(s)	Ti(s)
$\Delta H_f^{\ominus}$/ kJ mol^{-1}	–720	+3	–411	0

(i) State why the value for the standard enthalpy of formation of Na(l) is **not** zero.

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(1)

(ii) Use data from the table to calculate a value for the standard enthalpy change of the following reaction.

$$TiCl_4(g) + 4Na(l) \longrightarrow 4NaCl(s) + Ti(s)$$

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(3)

(iii) State the role of sodium in this reaction.

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(1)

(Total 11 marks)

Q14. (a) Iron is extracted from iron(III) oxide using carbon at a high temperature.

(i) State the type of reaction that iron(III) oxide undergoes in this extraction.

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(1)

(ii) Write a half-equation for the reaction of the iron(III) ions in this extraction.

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(1)

(b) At a high temperature, carbon undergoes combustion when it reacts with oxygen.

(i) Suggest why it is **not** possible to measure the enthalpy change directly for the following combustion reaction.

$$C(s,graphite) + \frac{1}{2}O_2(g) \longrightarrow CO(g)$$

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(1)

(ii) State Hess's Law.

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(1)

(iii) State the meaning of the term *standard enthalpy of combustion.*

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(Extra space) .....

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(3)

(c) Use the standard enthalpies of formation in the table below and the equation to calculate a value for the standard enthalpy change for the extraction of iron using carbon monoxide.

	$Fe_2O_3(s)$	CO(g)	Fe(l)	$CO_2(g)$
$\Delta H_f^{\ominus}$/ kJ mol^{-1}	– 822	– 111	+14	– 394

$$Fe_2O_3(s) + 3CO(g) \longrightarrow 2Fe(l) + 3CO_2(g)$$

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(Extra space) .....

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(3)

(d) (i) Write an equation for the reaction that represents the standard enthalpy of formation of carbon dioxide.

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(1)

(ii) State why the value quoted in part (c) for the standard enthalpy of formation of $CO_2(g)$ is the same as the value for the standard enthalpy of combustion of carbon.

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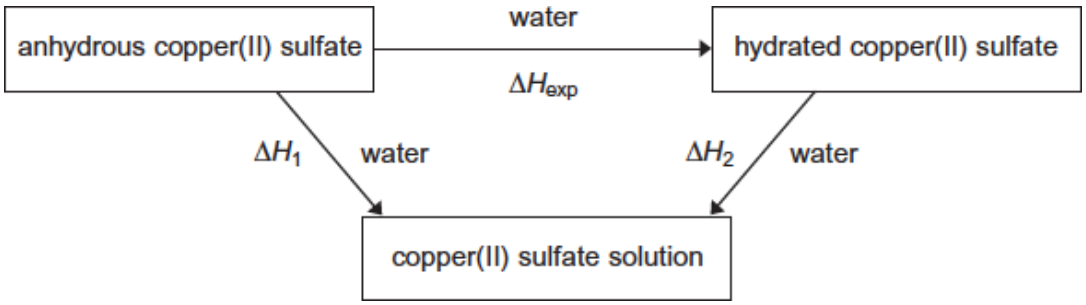
(1)
(Total 12 marks)

Q15. A student used Hess's Law to determine a value for the enthalpy change that occurs when anhydrous copper(II) sulfate is hydrated. This enthalpy change was labelled ΔH_{exp} by the student in a scheme of reactions.



(a) State Hess's Law.

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(1)

(b) Write a mathematical expression to show how ΔH_{exp}, ΔH_1 and ΔH_2 are related to each other by Hess's Law.

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(1)

(c) Use the mathematical expression that you have written in part (b), and the data book values for the two enthalpy changes ΔH_1 and ΔH_2 shown, to calculate a value for ΔH_{exp}

$\Delta H_1 = -156$ kJ mol^{-1}

$\Delta H_2 = +12$ kJ mol^{-1}

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(1)

(d) The student added 0.0210 mol of pure anhydrous copper(II) sulfate to 25.0 cm^3 of deionised water in an open polystyrene cup. An exothermic reaction occurred and the temperature of the water increased by 14.0 °C.

(i) Use these data to calculate the enthalpy change, in kJ mol^{-1}, for this reaction of copper(II) sulfate. This is the student value for ΔH_1

In this experiment, you should assume that all of the heat released is used to raise the temperature of the 25.0 g of water. The specific heat capacity of water is 4.18 J K^{-1} g^{-1}.

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(3)

(ii) Suggest **one** reason why the student value for ΔH_1 calculated in part (d)(i) is less accurate than the data book value given in part (c).

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(1)

(e) Suggest **one** reason why the value for ΔH_{exp} **cannot** be measured directly.

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(Extra space) .....

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(1)
(Total 8 marks)

Q16. This question is about the extraction of metals.

(a) Manganese can be extracted from Mn_2O_3 by reduction with carbon monoxide at high temperature.

(i) Use the standard enthalpy of formation data from the table and the equation for the extraction of manganese to calculate a value for the standard enthalpy change of this extraction.

	$Mn_2O_3(s)$	CO(g)	Mn(s)	$CO_2(g)$
$\Delta H_f^{\ominus}$ / kJ mol^{-1}	−971	−111	0	−394

$$Mn_2O_3(s) + 3CO(g) \longrightarrow 2Mn(s) + 3CO_2(g)$$

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(3)

(ii) State why the value for the standard enthalpy of formation of Mn(s) is zero.

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(1)

(b) Titanium is extracted in industry from titanium(IV) oxide in a two-stage process.

(i) Write an equation for the first stage of this extraction in which titanium(IV) oxide is converted into titanium(IV) chloride.

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(2)

(ii) Write an equation for the second stage of this extraction in which titanium(IV) chloride is converted into titanium.

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(2)

(c) Chromium is extracted in industry from chromite ($FeCr_2O_4$).

(i) In the first stage of this extraction, the $FeCr_2O_4$ is converted into Na_2CrO_4 Balance the equation for this reaction.

.....$FeCr_2O_4$ + ...Na_2CO_3 + ...O_2 ⟶ .....Na_2CrO_4 + $2Fe_2O_3$ + $8CO_2$

(1)

(ii) In the final stage, chromium is extracted from Cr_2O_3 by reduction with aluminium.

Write an equation for this reaction.

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(1)

(Total 10 marks)

Q17. Group 2 metals and their compounds are used commercially in a variety of processes.

(a) Strontium is extracted from strontium oxide (SrO) by heating a mixture of powdered strontium oxide and powdered aluminium.

Consider these standard enthalpies of formation.

	SrO(s)	$Al_2O_3(s)$
$\Delta H_f^{\ominus}$ / kJ mol^{-1}	– 590	– 1669

$$3SrO(s) + 2Al(s) \longrightarrow 3Sr(s) + Al_2O_3(s)$$

Use these data and the equation to calculate the standard enthalpy change for this extraction of strontium.

The use of powdered strontium oxide and powdered aluminium increases the surface area of the reactants.
Suggest **one** reason why this increases the reaction rate.

Suggest **one** major reason why this method of extracting strontium is expensive.

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(5)

(b) Explain why calcium has a higher melting point than strontium.

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(2)

(c) Magnesium is used in fireworks. It reacts rapidly with oxygen, burning with a bright white light. Magnesium reacts slowly with cold water.

Write an equation for the reaction of magnesium with oxygen.

Write an equation for the reaction of magnesium with cold water.

Give a medical use for the magnesium compound formed in the reaction of magnesium with cold water.

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(3)
(Total 10 marks)