Winter 2025 **Chemistry 2000 Final Exam** ____/ 120 marks

Confidentiality Agreement:
I agree not to discuss (or in any other way divulge) the contents of this exam with (or in the presence of) any CHEM 2000 student who has yet to write it. I understand that breaking this agreement would constitute academic misconduct. The minimum penalty would be a mark of 0/120 on this exam.

Signature: _____ Date: _____

1) Please read the test carefully before starting. It has 13 pages of questions (seven pages double-sided).
2) You have also been given a data sheet. It does not have a QR code, so nothing written on it will be graded.
3) **DO NOT WRITE ON ANY QR CODE!!!** Work on pages without a QR code will not be graded.
4) You may use a calculator but only for calculation. No other electronic devices are allowed. Any non-trivial use of a calculator must be described. For example, if you use a calculator to solve a nonlinear equation, you need to make it clear what equation was solved and provide any other inputs you used to the calculation.
5) If your work is not legible, it will be given a mark of zero.
6) Show your work. Answers without supporting reasoning or calculations will not get full credit
7) Marks will be deducted for incorrect information added to an otherwise correct answer.
8) Marks will be deducted for improper use of significant figures and for missing or incorrect units. Show units in every step of all calculations. Significant figures will only be checked in final answers. If a question has subparts (a, b, c, etc.), the answer to each subpart is considered a "final answer".
9) You have 3 hours to complete this test.

Question Breakdown

Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12						Total
/ 10	/ 12	/ 6	/ 10	/ 8	/ 5	/ 19	/ 14	/ 13	/ 18	/ 4	/ 1						/ 120

1. Fill in each blank with the word or phrase that best completes the sentence. **[10 marks]**
Where options are provided in brackets after a blank, choose one of those options to fill in the blank.

(a) The conjugate acid of H_2S is _H_3S^+_.

(b) The conjugate base of H_2S is _HS^-_.

(c) When a nonvolatile substance is dissolved in a liquid, the boiling point of the liquid _increases_ *(increases or decreases or stays the same)*.

(d) When comparing the same substance at the same temperature in different phases, the entropy will be highest for the substance in the _gas_ *(solid or liquid or gas)* phase.

(e) When comparing the same substance in the same phase at different temperatures, the entropy will be highest for the substance at the _higher_ *(higher or lower)* temperature.

(f) When a reaction has $\Delta H > 0$ and $\Delta S > 0$, it will be thermodynamically favoured in the forward direction at _high_ *(high or low or all or no)* temperatures.

(g) When a reaction has $\Delta H > 0$ and $\Delta S < 0$, it will be thermodynamically favoured in the forward direction at _no_ *(high or low or all or no)* temperatures.

(h) When a reaction is thermodynamically favoured in the forward direction, _$Q < K$_ *(Q<K or Q=K or Q>K)*.

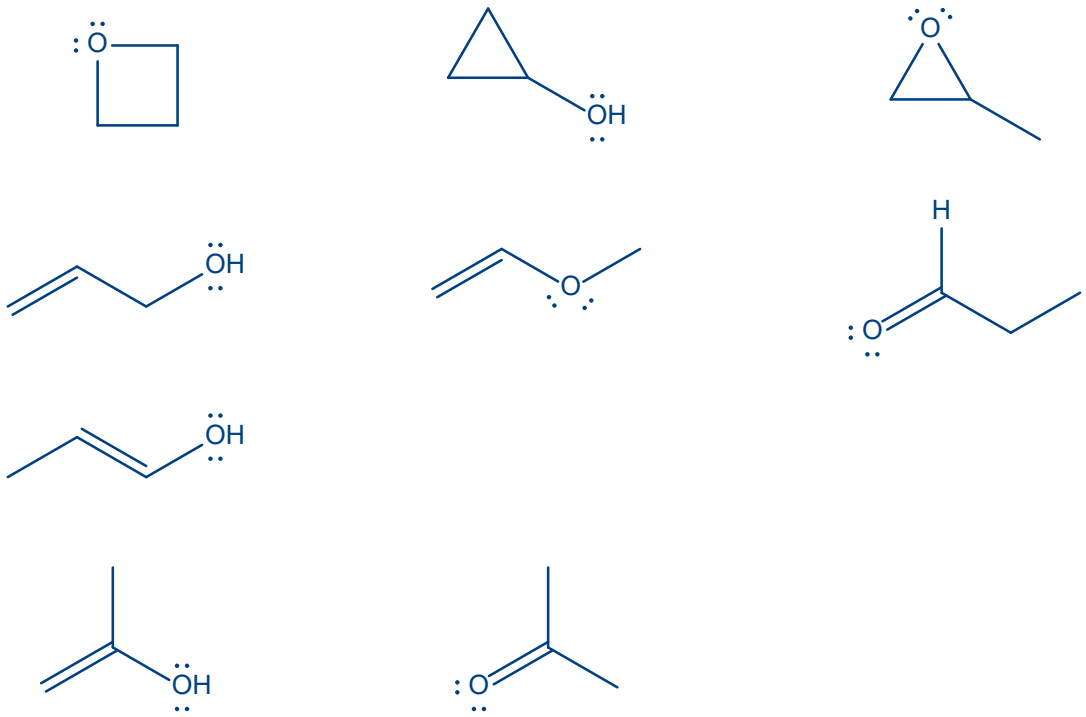
(i) When equilibrium has been reached, which of the following is true? *Circle the answer.*

$\Delta G = 0$ $\quad \Delta G° = 0$ $\quad \Delta H = 0$ $\quad \Delta H° = 0$ $\quad \Delta S = 0$ $\quad \Delta S° = 0$

(j) If the pK_a of H_2CO_3 is 6.3 and the pK_a of HCO_3^- is 10.3, then the pH of an aqueous solution containing equal concentrations of H_2CO_3 and HCO_3^- will be _6.3_.

2. This series of questions deals with molecules having the formula $\boldsymbol{C_3H_6O}$. Use your knowledge of organic chemistry principles to answer the following: **[12 marks]**

(a) Draw all the **structural** isomers of $\boldsymbol{C_3H_6O}$. Duplicate or incorrect structures will result in a deduction of marks. You may use any format for drawing your structures as long as you are consistent. *[9 marks]*



(b) Geometric isomers are also called *cis*- *trans*- isomers. Identify **one** structure you listed from part (a) that can exhibit geometric isomerism. Draw the two isomers below and label which is ***cis*** and which is ***trans***. [*3 marks]*

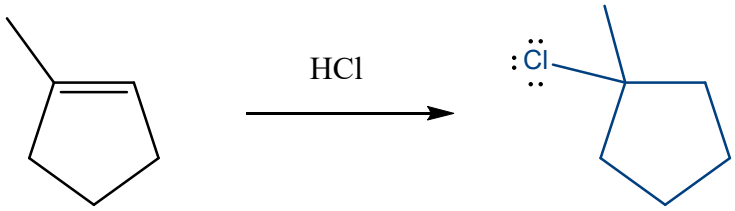


trans *cis*

3. Draw the major organic product for each of the following reactions. **[6 marks]**

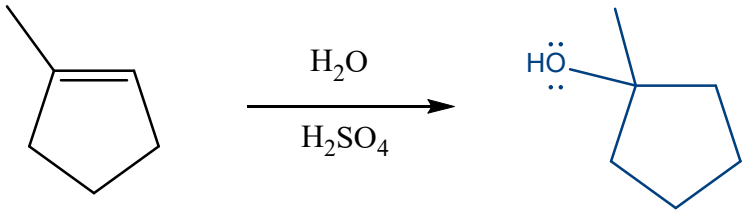
In cases where the reaction produces a specific stereoisomer of product, clearly show the stereochemistry of the product.

(a)



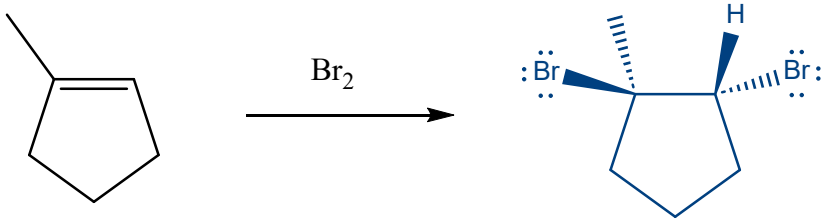
Markovnikov addition, so Cl is attached to the more substituted carbon atom while H is attached to the carbon that already has more H attached.

(b)



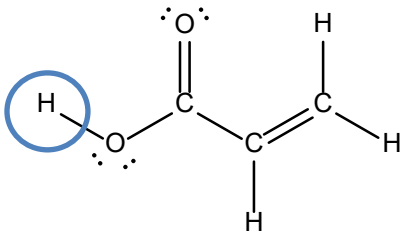
Markovnikov addition, so OH is attached to the more substituted carbon atom while H is attached to the carbon that already has more H attached.

(c)

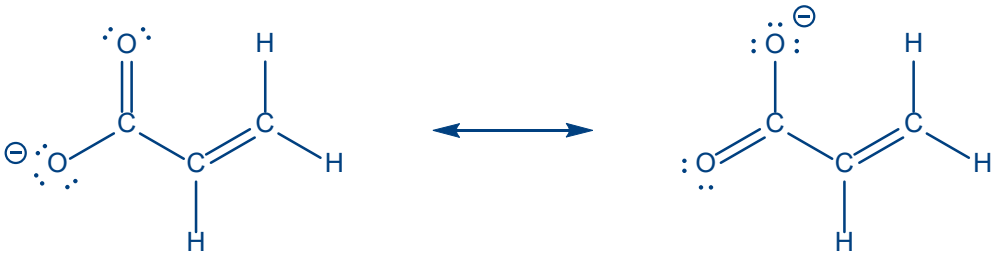


Because of the bromonium ion intermediate, the two bromine atoms have a trans relationship in the product.

4. Consider the following molecule: **[10 marks]**



(a) This molecule is an acid. Circle the acidic hydrogen atom on the diagram above and explain your choice. Your explanation must include a drawing of the conjugate base and any other relevant drawings. *[4 marks]*



The conjugate base for this acid is shown above. Deprotonation of any hydrogen atom other than the one that was circled above would give a much less favourable conjugate base.

The conjugate base shown above:

- has the negative charge on oxygen atoms, which are the most electronegative atoms in the molecule
- has the negative charge shared by two oxygen atoms such that each only has a charge of -0.5 (as shown in the resonance structures above)

(b) The pK_a of this acid is 4.25. Calculate the pH of a 0.25 M aqueous solution of this acid at 25°C. *[6 marks]*

Step 1: Set up ICE table

	$HA_{(aq)}$	$\rightleftharpoons$	$H^+_{(aq)}$	$+$	$A^-_{(aq)}$
I (M)	0.25		10^{-7}		0
C (M)	$-x$		$+x$		$+x$
E (M)	$0.25 - x \approx 0.25$		$10^{-7} + x \approx x$		x

Step 2: Calculate K_a from pK_a

$$pK_a = -logK_a$$
$$K_a = 10^{-pK_a} = 10^{-4.25} = 5.6 \times 10^{-5}$$

Step 3: Calculate x

$$K_a = \frac{(a_{H^+})(a_{A^-})}{a_{HA}}$$
$$5.6 \times 10^{-5} = \frac{(x)(x)}{0.25}$$
$$(5.6 \times 10^{-5})(0.25) = x^2$$
$$x = \sqrt{(5.6 \times 10^{-5})(0.25)}$$
$$x = 0.0037$$

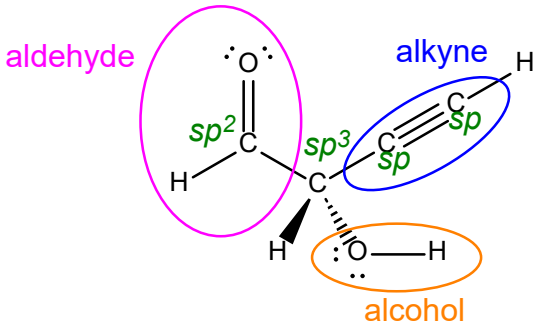
Step 4: Check assumptions

Assumption #1: $10^{-7} + \boldsymbol{x} \approx x$	$10^{-7} + 0.0037 = 0.0037$	assumption is okay
Assumption #2: $0.25 - \boldsymbol{x} \approx 0.25$	$0.25 - 0.0037 = 0.2463 = 0.25$	assumption is okay

Step 5: Calculate pH from a_{H^+}

$$a_{H^+} = x = 0.0037$$
$$pH = -log(a_{H^+}) = -log(0.0037) = 2.43$$

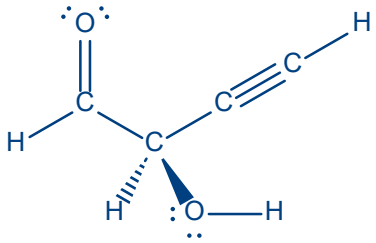
5. Consider the following molecule: **[8 marks]**



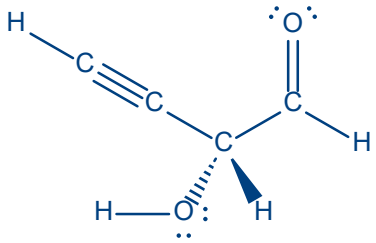
(a) Beside each carbon atom, label its hybridization. *[4 marks]*

(b) Circle and name each functional group in the molecule. *[3 marks]*

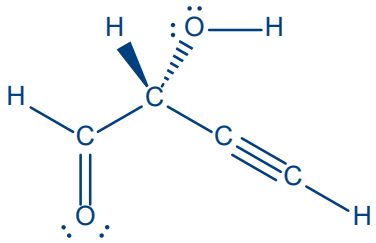
(c) Draw the enantiomer of this molecule in the space below. *[1 mark]*



or



or

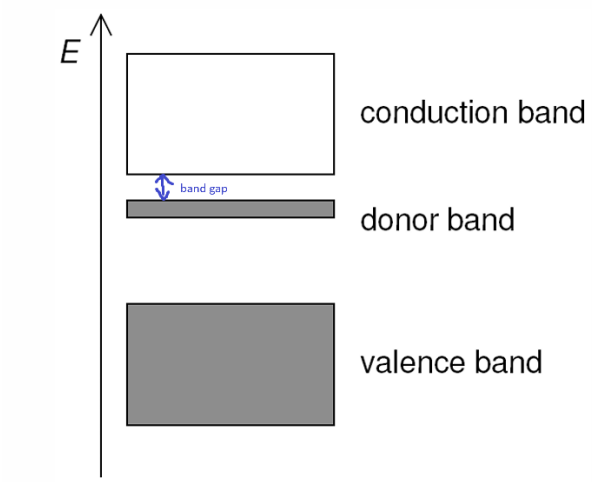


6. A material contains 99% germanium (Ge) atoms with 1% arsenic (As) atoms distributed throughout the lattice. **[5 marks]**

(a) Classify this material as a conductor, an insulator, an inherent semiconductor, an n-type semiconductor or a p-type semiconductor. *[1 mark]*

n-type semiconductor

(b) Draw a band diagram for this material. Clearly label the valence band, conduction band, any other relevant bands and the band gap. Use shading to make it clear whether each band is fully occupied, partially occupied or unoccupied. *[4 marks]*



7. **[19 marks]**

(a) Draw a Lewis diagram for NO^+. Your diagram must show any non-zero formal charges. *[1 mark]*



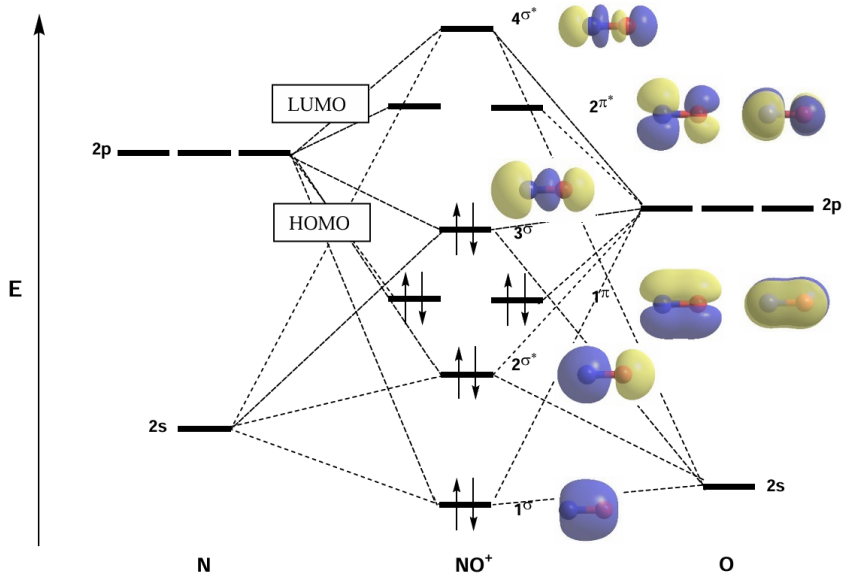
(b) With which homonuclear diatomic molecule is NO^+ isoelectronic? *[1 mark]*

N_2

(c) Draw a valence molecular orbital energy level diagram (MO diagram) for NO^+. *[13 marks]*

Your diagram must include:

- molecular orbital energy levels labeled using the convention taught in CHEM 2000 that communicates symmetry (σ or π) as well as bonding character (bonding, nonbonding or antibonding)
- electrons in the appropriate molecular orbitals
- a drawing of each molecular orbital, showing its shape, orientation and relative phases



(d) Calculate the bond order for NO^+ based on your MO diagram. How does it compare to the bond order shown by your Lewis diagram? *[2 marks]*

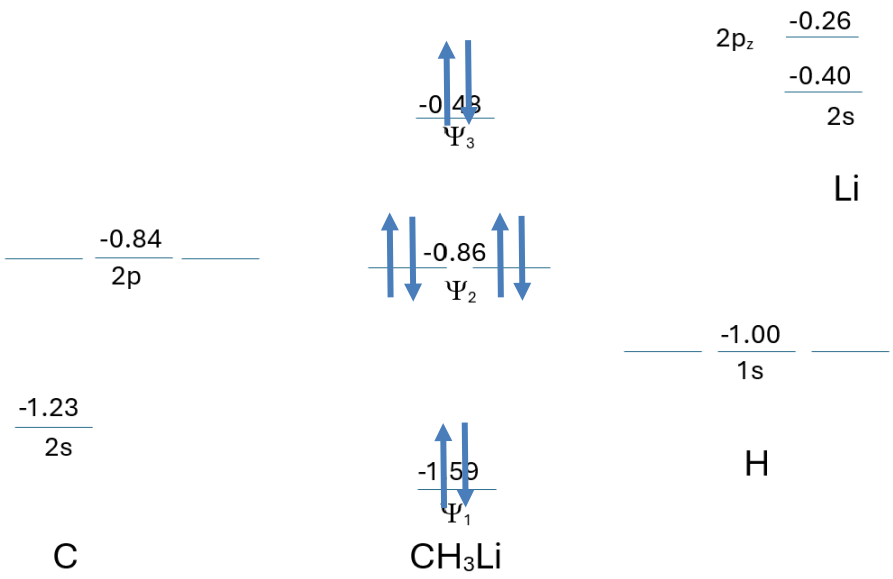
$BO = \frac{1}{2}(bonding\ e^- - antibonding\ e^-) = \frac{1}{2}(8-2) = \frac{1}{2}(6) = 3$

This is consistent with the triple bond in the Lewis diagram.

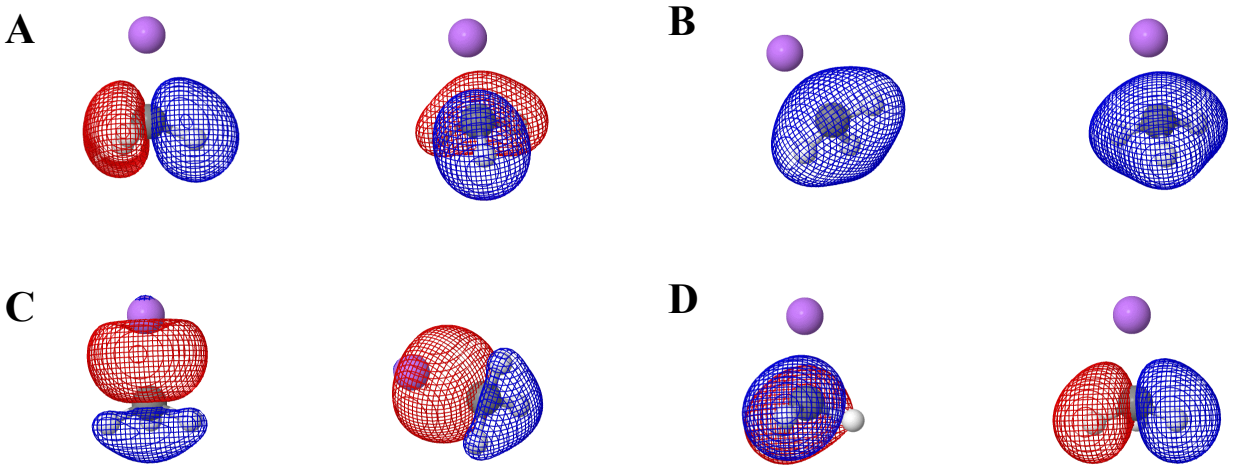
(e) Energy levels of the molecular orbitals in a cation are lower than those for the corresponding molecular orbitals in the corresponding neutral compound. As such, all valence molecular orbitals in NO^+ have negative energy values. Knowing this, explain why it is the case that NO can form from NO^+ but NO^- will not readily form from NO. *[2 marks]*

The LUMO of NO^+ has a negative energy, so it is favourable to add an electron into it. Doing so, however, raises the energy of all MOs such that addition of another electron would no longer be to an MO with negative energy and, as such, addition of the second electron (making NO^- from NO) would not be favourable.

8. The partial MO diagram below shows the four lowest energy valence molecular orbitals of CH_3Li. **[14 marks]**



The diagrams below show drawings of Ψ_1, Ψ_2 and Ψ_3. Each molecular orbital is shown from two different angles (front view and side view).



(a) For each pair of drawings, identify the corresponding molecular orbital (Ψ_1, Ψ_2 or Ψ_3). *[4 marks]*

A is ___Ψ_2___ **B** is ___Ψ_1___ **C** is ___Ψ_3___ **D** is ___Ψ_2___

(b) Populate the partial MO diagram with the appropriate number of electrons in the molecular orbitals. *see MO diagram above* *[1 mark]*

continued on next page…

8. *…continued from previous page*

(c) Which molecular orbital is most relevant to the behavior of CH_3Li as a nucleophile? Your answer should indicate **both** whether it is the HOMO or the LUMO **and** the specific molecular orbital (Ψ_1, Ψ_2 or Ψ_3). *[2 marks]*

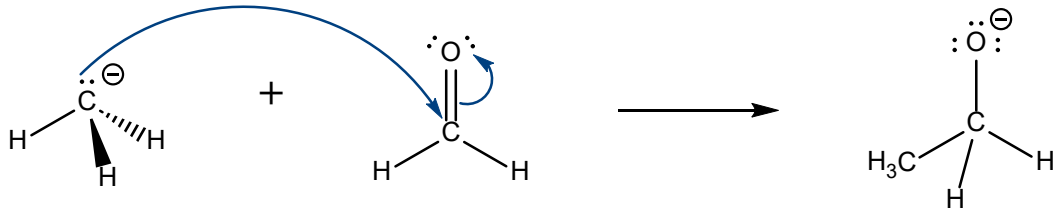
Nucleophiles react via the HOMO which, for this molecule, is Ψ_3.

(d) Organic chemists often consider CH_3Li to behave as the nucleophilic carbanion CH_3^-. How is the shape of the orbital identified in your answer to part (c) consistent with viewing CH_3Li this way? *[2 marks]*

Hint: You will need to consider which atomic orbital(s) formed this molecular orbital.

The shape of Ψ_3 is very similar to that of a $2p$ orbital on the carbon atom which is where you'd expect to see the lone pair in : CH_3^-.

(e) Complete the diagram below showing the reaction between CH_3Li and CH_2O by adding curved arrows to show the movement of electrons. *[2 marks]*



(f) For the reaction shown above, into which molecular orbital must CH_2O accept the electron pair – into its HOMO or into its LUMO? Based on the reactants and products shown above, what must the symmetry and bonding character be for that molecular orbital? How do you know? *[3 marks]*

Electrons are accepted into a molecule's LUMO. Since this reaction results in conversion of a $C = O$ double bond to a $C - O$ single bond, a $C - O$ pi bond must be broken so the LUMO must be a π^* MO.

9. Typical rock minerals are composed of silicates of iron, calcium, potassium and aluminum. Consider the mineral Koalinite $(Al_2SiO_{5(s)})$ which reacts with CO_2 in the atmosphere as follows: **[13 marks]**

$$Al_2SiO_{5(s)} + 3\ CO_{2(g)} \rightleftharpoons Al_2(CO_3)_{3(s)} + SiO_{2(s)} \qquad \textbf{(I)}$$

$Al_2(CO_3)_{3(s)}$ is extremely unstable and therefore reacts quickly with atmospheric water vapor as follows:

$$Al_2(CO_3)_{3(s)} + 3\ H_2O_{(g)} \rightleftharpoons 2\ Al(OH)_{3(s)} + 3\ CO_{2(g)} \qquad \textbf{(II)}$$

Finally, the $Al(OH)_{3(s)}$ dehydrates to form $Al_2O_{3(s)}$:

$$2\ Al(OH)_{3(s)} \rightleftharpoons Al_2O_{3(s)} + 3\ H_2O_{(g)} \qquad \textbf{(III)}$$

(a) Write a balanced chemical equation for the combined reactions **I** and **II**. *[1 mark]*

$Al_2SiO_{5(s)} + 3\ H_2O_{(g)} \rightleftharpoons 2\ Al(OH)_{3(s)} + SiO_{2(s)}$

(b) Calculate the standard free energy change for the combined reactions **I** and **II**. *[2 marks]*

$\Delta_r G° = \sum \Delta_f G°(products) - \sum \Delta_f G°(reactants)$

$\Delta_r G° = \left[2\ \Delta_f G°\left(Al(OH)_{3(s)}\right) + \ \Delta_f G°\left(SiO_{2(s)}\right)\right] - \left[\Delta_f G°\left(Al_2SiO_{5(s)}\right) + 3\ \Delta_f G°\left(\ H_2O_{(g)}\right)\right]$

$\Delta_r G° = \left[2\left(-1284.56\frac{kJ}{mol}\right) + \ \left(-855.88\frac{kJ}{mol}\right)\right] - \left[\left(-2443.87\frac{kJ}{mol}\right) + 3\left(-228.60\frac{kJ}{mol}\right)\right]$

$\Delta_r G° = -295.33\frac{kJ}{mol}$

(c) Calculate the equilibrium constant for reaction **III** at 25°C. *[4 marks]*

Step 1: Calculate standard free energy change for reaction III

$\Delta_r G° = \sum \Delta_f G°(products) - \sum \Delta_f G°(reactants)$

$\Delta_r G° = \left[\Delta_f G°\left(Al_2O_{3(s)}\right) + \ 3\ \Delta_f G°\left(\ H_2O_{(g)}\right)\right] - \left[2\ \Delta_f G° Al(OH)_{3(s)}\right]$

$\Delta_r G° = \left[\left(-1656.86\frac{kJ}{mol}\right) + \ 3\left(-228.60\frac{kJ}{mol}\right)\right] - \left[2\left(-1284.56\frac{kJ}{mol}\right)\right]$

$\Delta_r G° = 226.46\frac{kJ}{mol}$

Step 2: Calculate equilibrium constant for reaction III

$\Delta_r G° = -RTlnK$

$lnK = -\frac{\Delta_r G°}{RT}$

$lnK = -\frac{\left(226.46\frac{kJ}{mol}\right)}{\left(8.314\ 462\frac{J}{mol \cdot K}\right)(298.15\ K)} \times \frac{1000\ J}{1\ kJ}$

$lnK = -91.353$

$K = e^{-91.353}$

$K = 2.12 \times 10^{-40}$

(d) Write a balanced chemical equation for the combined reactions **I**, **II** and **III**. *[1 mark]*

$Al_2SiO_{5(s)} \rightleftharpoons Al_2O_{3(s)} + SiO_{2(s)}$

(e) Write the equilibrium constant expression for the combined reactions **I**, **II** and **III**. What must the equilibrium constant always be? Why? *[3 marks]*

$K = \frac{(a_{Al_2O_{3(s)}})(a_{SiO_{2(s)}})}{a_{Al_2SiO_{5(s)}}} = \frac{(1)(1)}{1} = 1$

Because all products and reactants are solids, they all have activities equal to 1 so the equilibrium constant must be 1.

(f) Keeping in mind answers to previous parts of this question, why would it take 5000 years for 50% of this mineral to erode? *[1 mark]*

The reactant is a solid and reaction can only occur at the surface of the solid. The products are also solids, so they will coat the surface of the solid reactant, reducing its exposure to the carbon dioxide and/or water vapour required for reaction. Essentially, they will form a passivation layer over the Kaolinite. As such, further reaction will only be possible after the products are physically rubbed off the mineral.

(g) What is the term describing the role of the carbon dioxide in the overall reaction (i.e. combined reactions **I**, **II** and **III**)? *[1 mark]*

catalyst

10. Consider the unbalanced reaction equations below and answer the following questions to help you evaluate whether hearing aid batteries are better than lithium ion batteries: **[18 marks]**

$$___\ Li_{(s)} + ___\ O_{2(g)} + ___\ H_2O_{(l)} \rightarrow ___\ LiOH_{(aq)} \qquad \textbf{(I)}$$

$$_4_\ Li_{(s)} + ___\ O_{2(g)} + _2_\ H_2O_{(g)} \rightarrow _4_\ LiOH_{(s)} \qquad \textbf{(II)}$$

(a) Balance reaction **I** using the method of half reactions. *[5 marks]*

For full credit, you must show both balanced half reactions and label which occurs at the cathode and which occurs at the anode.

Oxidation at anode: $Li_{(s)} + OH^-_{(aq)} \rightarrow LiOH_{(aq)} + e^-$

Reduction at cathode: $O_{2(g)} + 2\,H_2O_{(l)} + 4\,e^- \rightarrow 4\,OH^-_{(aq)}$

Overall reaction: $4\,Li_{(s)} + O_{2(g)} + 2\,H_2O_{(l)} \rightarrow 4\,LiOH_{(aq)}$ $\qquad \nu_e = 4$

(b) Using the half-cell potentials provided, calculate the standard cell potential for reaction **I**. *[2 marks]*

$E° = (+0.401\,V) + (+3.045\,V) = +3.446\,V$ *or* $E° = (+0.401\,V) - (-3.045\,V) = +3.446\,V$

(c) Using the standard free energies of formation provided, calculate the standard cell potential for reaction **II**. *[4 marks]*

Step 1: Calculate standard free energy change for reaction II

$$\Delta_r G° = \sum \Delta_f G°(products) - \sum \Delta_f G°(reactants)$$

$$\Delta_r G° = \left[4\,\Delta_f G°\left(LiOH_{(s)}\right)\right] - \left[4\,\Delta_f G°\left(Li_{(s)}\right) + \Delta_f G°\left(O_{2(g)}\right) + 2\,\Delta_f G°\left(H_2O_{(g)}\right)\right]$$

$$\Delta_r G° = \left[4\left(-438.90\,\frac{kJ}{mol}\right)\right] - \left[4\left(0\,\frac{kJ}{mol}\right) + \left(0\,\frac{kJ}{mol}\right) + 2\left(-228.60\,\frac{kJ}{mol}\right)\right]$$

$$\Delta_r G° = -1298.40\,\frac{kJ}{mol}$$

Step 2: Calculate standard cell potential for reaction II

$$\Delta_r G° = -\nu_e F E°$$

$$E° = -\frac{\Delta_r G°}{\nu_e F}$$

$$E° = -\frac{\left(-1298.40\frac{kJ}{mol}\right)}{(4)\left(96485\,\frac{C}{mol}\right)} \times \frac{1000\,J}{1\,kJ} \times \frac{1\,V}{1\,\frac{J}{C}} = +3.3643\,V$$

(d) Calculate the cell potential of the solid-state battery (reaction **II**) at sea level where $p_{H_2O} = 0.032\ bar$ and $p_{O_2} = 0.21\ bar$ on a 30°C day. *[4 marks]*

Step 1: Calculate reaction quotient (Q)

$$Q = \frac{\left(a_{LiOH_{(s)}}\right)^4}{\left(a_{Li_{(s)}}\right)^4\left(a_{O_{2(g)}}\right)\left(a_{H_2O_{(g)}}\right)^2}$$

$$Q = \frac{(1)^4}{(1)^4(0.21)(0.032)^2}$$

$$Q = 4650 \quad \textit{(with 2 sig. fig.)}$$

Step 2: Use Nernst equation to calculate cell potential

$$E = E° - \frac{RT}{\nu_e F} lnQ$$

$$E = (+3.3643\ V) - \frac{\left(8.314462\ \frac{J}{mol \cdot K}\right)(303.15\ K)}{(4)\left(96485\ \frac{C}{mol}\right)} \times \frac{1V}{1\frac{J}{C}} \times ln(4650)$$

$$E = (+3.3643\ V) - (0.0552\ V)$$

$$E = +3.3091\ V$$

(e) If a solid-state battery described in part (d) has an initial mass of 1 kg (i.e. contains 1 kg of lithium metal), what is the maximum amount of energy it can produce in kWh? *[2 marks]*

Step 1: Calculate moles of electrons, recognizing that each mole of Li can lose 1 mole of electrons

$$n_e = n_{Li} = \frac{m}{M} = \frac{1000\ g}{6.941\frac{g}{mol}} = 1 \times 10^2\ mol \quad \textit{(with 1 sig. fig.}$$

Step 2: Calculate total charge of electrons

$$q = (1 \times 10^2\ mol)\left(96485\ \frac{C}{mol}\right) = 1 \times 10^7 C$$

Step 3: Calculate energy from potential and charge, remembering that $1\ V = 1\ \frac{J}{C}$

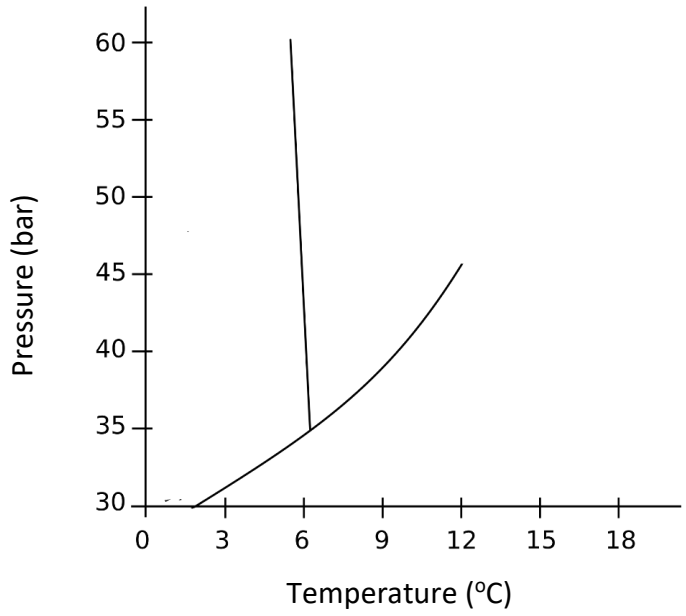
$$E = (1 \times 10^7 C)\left(3.3091\ \frac{J}{C}\right) = 5 \times 10^7 J$$

$$E = (5 \times 10^7 J)\left(\frac{1\ MJ}{10^6\ J}\right)\left(\frac{1\ kWh}{3.6\ MJ}\right) = 1 \times 10^1 kWh$$

(f) A typical lithium-ion car battery that can produce 1 kWh weighs 6 kg. If you have two batteries (a lithium-ion battery and a solid-state lithium oxide battery (reaction **II**)) that both produce the same amount of energy, which one will weigh less? Why is this important if you want to use the battery to power a vehicle? *[1 mark]*

The solid-state battery produces $\sim 13\ \frac{kWh}{kg}$ while the lithium-ion battery produces $\sim \frac{1}{6}\frac{kWh}{kG}$. As such, you could travel the same distance using a much lighter solid-state battery.

11. Circle the correct word in each bracket in accordance with the phase diagram below. **[4 marks]**



(a) The **(critical / triple)** point is at 35 bar and 6°C.

(b) Increasing the temperature from 1°C at a constant pressure of 32 bar will result in **(fusion / sublimation)**.

(c) The slight negative slope of the straight line in the phase diagram means you can induce freezing by **(compressing / decompressing)** the liquid form of the substance.

(d) At 35 bar and 18°C, the substance exists in the **(gaseous / supercritical)** state.

12. What was the most useful and/or interesting thing you learned in CHEM 2000? **[1 mark]**

…AND THAT'S ALL FOR CHEM 2000.
HAVE A GREAT SUMMER!