22TTC202

Battery Technology

Semester 2 2022/23 | In-Person Exam paper

This examination is to take place in-person at a central University venue under exam conditions. The standard length of time for this paper is **2 hours**.

You will not be able to leave the exam hall for the first 30 or final 15 minutes of your exam. Your invigilator will collect your exam paper when you have finished.

Help during the exam

Invigilators are not able to answer queries about the content of your exam paper. Instead, please make a note of your query in your answer script to be considered during the marking process.

If you feel unwell, please raise your hand so that an invigilator can assist you.

You may use a calculator for this exam. It must comply with the University's Calculator Policy for In-Person exams, in particular that it must not be able to transmit or receive information (e.g. mobile devices and smart watches are **not** allowed).

Answer **THREE** questions

A formula sheet and values of useful constants (i.e., Faraday constant) are supplied at the end of this exam paper

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1. A large cylindrical lithium-ion battery is being designed to have an accessible capacity of 25 Ah and an N/P ratio of 1.15. The positive electrode is to be Nickel-Manganese-Cobalt (NMC) and the negative electrode Carbon (graphite). Cell properties are given in Table Q1.

   (a) To improve the lifetime of the cell, the positive electrode is to be cycled only between 3.7 V and 4.2 V. Using Figure Q1, determine the corresponding lithiation range of the positive electrode. If this lithiation range corresponds to the accessible capacity of the electrode, what is the theoretical capacity of the electrode? [3 marks]

   (b) If the positive electrode thickness is 120 µm, what is the thickness of the negative electrode? Assume the full lithiation range of the negative electrode is used. [4 marks]

   (c) If the height of the active material coating on the positive and negative electrodes are both 110 mm and the current collectors are coated on both sides, how long does the current collector coating need to be? [3 marks]

   (d) Battery cells can be manufacturing in three main formats, cylindrical, prismatic and pouch. Discuss the advantages and disadvantages of each of the different cell formats on the manufacturing and assembly of large battery packs for propulsion applications. In your answer consider the following:

   (i) Assembly process of the cell
   (ii) Assembly process of the battery pack
   (iii) Manufacturing throughput (speed) and cost
   (iv) Manufacturing reliability and tolerance

   [10 marks]

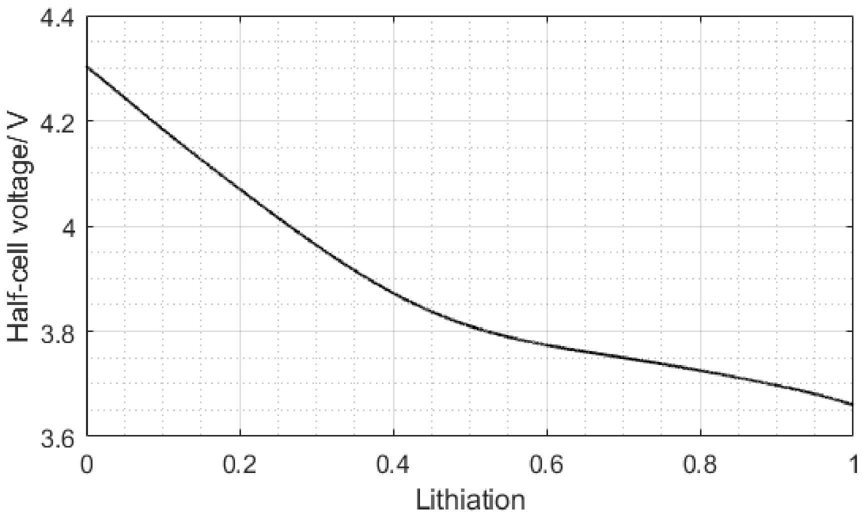

Figure Q1 – Half cell voltage profile of NMC positive electrode material

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Q1 Continued/…

Table Q1

Material	Specific capacity (mAh/g)	Packed density (g/cm^3)	Porosity (%)
Carbon (LiC_6)	372	1.8	20
NMC ($LiNi_8Mn_1Co_1O_2$)	200	2.3	18

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2. A lithium-ion battery with parameters detailed in Table Q2 undergoes the electrochemical reaction in equation Q2 during discharge.

$$Negative: \quad LiC_6 \rightarrow C_6 + Li^+ + e^-$$
$$Positive: \quad FePO_4 + Li^+ + e^- \rightarrow LiFePO_4$$
$$Overall: \quad LiC_6 + FePO_4 \rightarrow LiFePO_4$$

Equation Q2

(a) If the cell open circuit voltage is 3.6 V and it is discharged with a current density of 10 mA cm^{-2}, what are the voltage losses required to overcome the activation energy and electrical resistance at 25 °C? What is actual operating voltage of the cell? [2 marks]

(b) If the cell has a capacity of 3 Ah, what is the mass of lithium that will be transferred from one electrode to another during a full charge or discharge? [3 marks]

(c) During the manufacturing of the cell, an extra 250 mg of lithium is added on top of the amount calculated in Question 2b, to account for loss of lithium inventory (LLI) due to growth of the solid electrolyte interphase layer (SEI). If all this excess lithium is consumed in the first 10 cycles, what is the average capacity loss per cycle? [2 marks]

(d) The cell has an N/P ratio of 1.2, what is the maximum amount of degradation due to loss of active material on the negative electrode (LAM_{NE}) that may occur before the negative electrode becomes the limiting electrode? Assume there is no degradation on the positive electrode. Express your answer as a percentage loss from the original negative electrode capacity. [3 marks]

(e) The lithium-ion cell in Figure Q2 shows a battery undergoing a short duration pulse discharge test followed by a relaxation (rest) period. Figure Q2a shows the current input (negative current for discharge) and Figure Q2b shows the voltage output. Describe the processes happening inside the battery during the test that cause the voltage response seen in Figure Q2b from the current input. In your answer, consider the following:

(i) Internal behaviour of the cell in the different regions A, B and C in Figure Q2.
(ii) The different components in the battery cell and their influence on cell voltage.
(iii) Electrochemical behaviour and reaction kinetics.
(iv) Different transport mechanisms occurring and their time constants (response time).

[10 marks]

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Q2 Continued/…

Table Q2

Parameter	Value
Exchange current density	$1 \times 10^{-4}\ A\ cm^{-2}$
Charge transfer coefficient	0.5
Electrical resistance	$15\ \Omega\ cm^2$

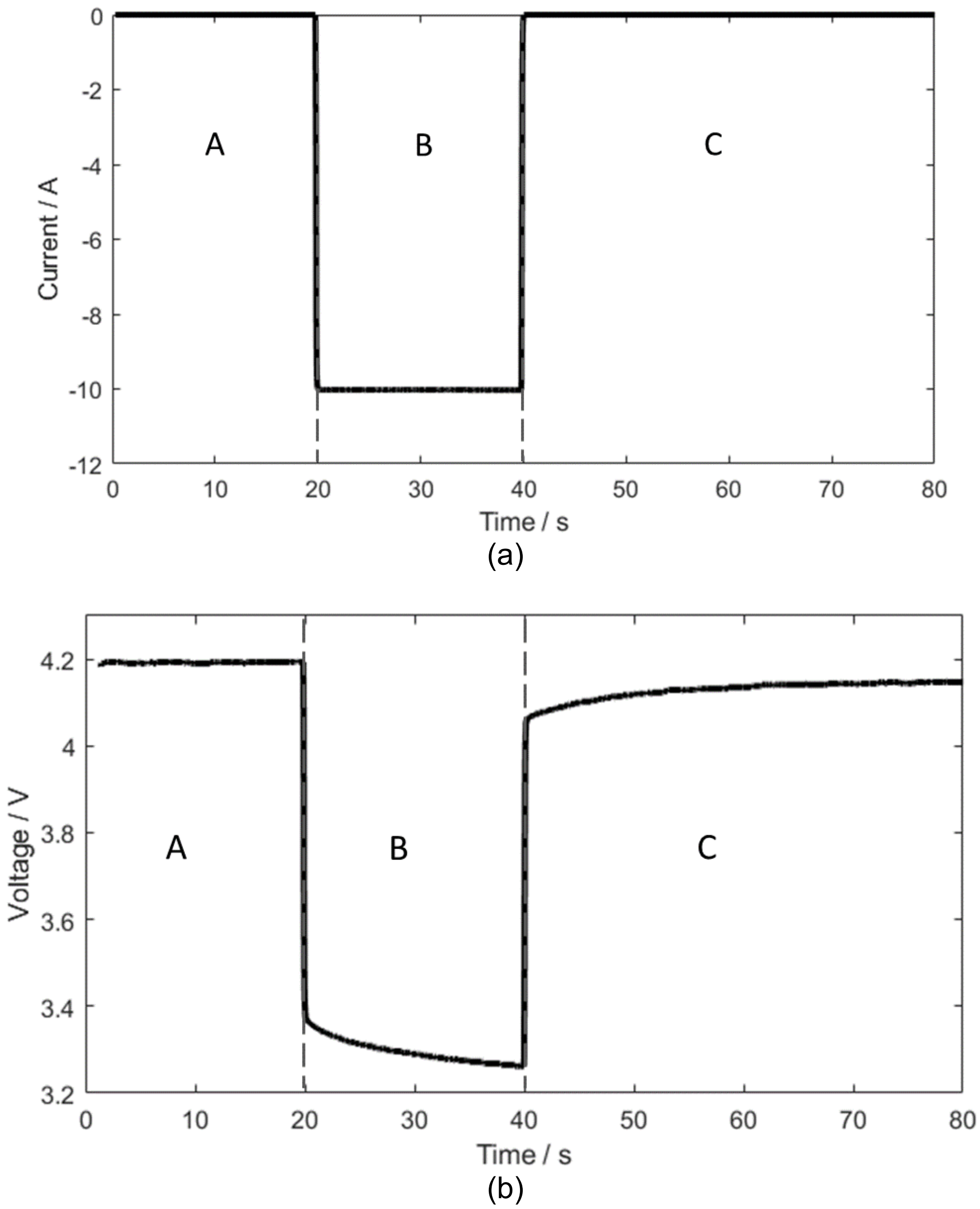

Figure Q2

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3. A battery pack is being designed to utilise cylindrical lithium-ion cells. Three potential cells are available with different geometry and electrochemical performance listed in Table Q3.

(a) The battery pack is required to deliver 500 kWh of energy and a peak discharge power of 1 MW. Which of the potential cells in Table Q3 will give the lightest battery pack and how many of each cell is required?

[4 marks]

(b) The pack is being designed for a 400 V system. Based on the nominal cell voltage, what is the series and parallel configuration of each cell type, how does this change the total number of cells required? [3 marks]

(c) Assuming the cells are packaged as shown in Figure Q3 and are single layer (i.e., cells are not placed on top of each other), which battery pack will occupy the smallest volume, what is the packaging efficiency of the battery (proportion of space occupied by cells)?

[4 marks]

(d) The open circuit voltage (OCV) of a lithium-ion battery changes with the cells state of charge (SOC). Explain why this happens, making reference to the electrochemical and thermodynamic behaviour of the electrodes. Also discuss how the choice of electrode material influences a batteries OCV and how the change in OCV can be used by a battery management system (BMS) for state estimation. [9 marks]

Table Q3

	Cell A	**Cell B**	**Cell C**
Energy (Wh)	9.6 Wh	16 Wh	50 Wh
Capacity (Ah)	3 Ah	5 Ah	20 Ah
Diameter (mm)	18	21	46
Height (mm)	65	70	80
Mass (g)	70	100	350
Maximum discharge C-rate	4.0	2.5	3.5
Nominal voltage (V)	3.6	3.6	3.25
Voltage at maximum discharge C-rate	3.7	3.7	3.3

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Q3 Continued/…

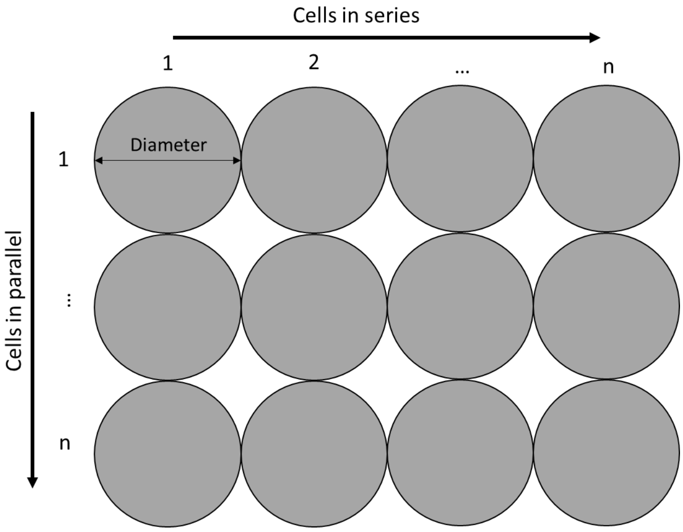

Figure Q3 – Example cell layout for 4s3p pack

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4. An all-electric aircraft is being designed for short duration flights. Initial battery testing shows that a current of 250 A is needed from the battery pack at 800 V for take-off.

(a) If the battery pack is to be designed using 52 Ah pouch cells that have a maximum discharge rate of 2C, what is the minimum number of cells required in parallel to deliver the maximum take of current? [2 marks]

(b) The aircraft requires 250 A for ten minutes and then 125 A for sustained flight. If the sustained flight section is to last 45 minutes, how many cells are needed in parallel, what is the minimum required pack capacity in Ah? [2 marks]

(c) The aircraft lands with 0% SOC then recharges at 90 A constant current. How long will the battery need to be charged to reach 80% SOC? [3 marks]

(d) If the aircraft now takes off with 80% SOC and requires the same current profile as Question 4b, what is the maximum sustained flight time? [3 marks]

(e) Many battery pack applications are recently making a switch in positive electrode material from either Nickel-Manganese-Cobalt (NMC) or Nickel-Cobalt-Aluminium (NCA) to Lithium-Iron-Phosphate (LFP). Discuss the reasoning behind this recent shift, referring to the electrochemical properties of the different electrode materials and their impact on cell and pack design. Which applications are better suited to NMC/NCA battery packs and which applications that are better suited to LFP positive electrode materials and why? In your answer you may want to consider:

(i) Energy / capacity
(ii) Cost / economics
(iii) Ethics
(iv) Safety
(v) Lifetime

[10 marks]

END OF PAPER

A Fly

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List of equations

$$Q = \frac{I}{nF}$$

$$\Delta G = \Delta H - T\Delta S$$

$$E^0 = -\frac{\Delta G^0}{nF}$$

$$V_{act} = \frac{RT}{\alpha nF} ln\left(\frac{i}{i_0}\right)$$

$$i = i_0\left[e^{\frac{\alpha nF}{RT}V_{act,1}} - e^{\frac{(1-\alpha)nF}{RT}V_{act,2}}\right]$$

$$V_{ohm} = iR_{elec}$$

$$i_{lim} = nFD_{AB}\frac{C_{anode} - C_{cathode}}{t_{electrolyte}}$$

$$P_v = \left[m_e\frac{dV}{dt} + \frac{1}{2}\rho AC_dV^2 + mg(A_d + B_dV) + mg(A_d + B_dV)\right]V + P_a$$

List of constants

Constant	**Value**
Faraday Constant	96485 C/mol
Universal gas constant	8.314 $J/molK$
Molar mass of lithium	6.941 $g\ /\ mol$
Gravitational constant	9.81 $m\,s^{-2}$

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