23TTC202
Battery Technology

Semester 2 2023/24 | 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.

1. A lithium-ion cell is being designed around a graphite negative electrode and nickel manganese cobalt (NMC) positive electrode. The properties of the cell are given in Table Q1, where the height and length are the same for both electrodes.

(a) What is the total capacity of the negative and positive electrode? [3 marks]

(b) If the positive electrode is the limiting electrode of the cell and is to be cycled between 0.05 and 0.9 levels of lithiation, what is the useable capacity of the cell? [2 marks]

(c) To give the correct lower voltage limit at 0% state of charge (SOC), the negative electrode must be at a lithiation level of 0.1 when the positive electrode is at 0.9. What is the lithiation level of each electrode at 75% SOC? [3 marks]

(d) As the cell ages, the relative lithiation of the electrodes shifts due to loss of lithium inventory (LLI). This means that now at 0% SOC, the negative electrode is at a lithiation level of 0.22 whereas the positive lithiation level remains unchanged at 0.9. Both electrode capacities remain unchanged. What is the new useable capacity of the cell if the negative electrode must not exceed the 1.0 maximum lithiation limit? [3 marks]

(e) Discuss how safety and reducing the risk of thermal runaway influences cell design, cell selection and battery pack/system design. In your answer, you may want to consider:

- Electrode material selection
- Cell level safety features
- Module and pack design
- Cell operation / BMS

[9 marks]

Table Q1

Material	**Parameter**	**Value**
Graphite	Specific capacity	375 mAh g^{-1}
	Packed Density	2.2 g cm^{-3}
	Porosity	20%
NMC ($LiNi_8Mn_1Co_1O_2$)	Specific capacity	210 mAh g^{-1}
	Packed Density	2.8 g cm^{-3}
	Porosity	25%
-	Negative electrode thickness	60 μm
-	Positive electrode thickness	85 μm
-	Electrode height	60 mm
-	Electrode length (coated both sides)	1250 mm

2. A battery pack is manufactured consisting of twenty 18650 cylindrical cells, each with a 3 Ah capacity and 3.6 V nominal voltage.

(a) If the nominal voltage of the battery pack is 14.4 V, what is the series/parallel configuration and capacity of the pack? [2 marks]

(b) The battery pack starts at 80% SOC and undergoes the duty cycle shown in Table Q2; what is the pack SOC and remaining capacity in the battery at the end of each stage? [4 marks]

(c) How many complete duty cycles can be conducted before the pack reaches 0% SOC? During which stage of the next incomplete duty cycle will the pack drop below 0% SOC? [2 marks]

(d) Over time, the battery pack ages and the pack capacity drops by 20%; what should the new minimum initial SOC be to complete the same number of complete duty cycles as Question 2c? Note: C-rate is based on the original capacity. [3 marks]

(e) The way in which a lithium-ion battery is operated will influence its rate of degradation and overall lifetime. Discuss different ways in which the operation and operating conditions of a lithium-ion battery can affect its rate of degradation whilst also considering the underlying causes of degradation (degradation mechanisms). In your answer, you may wish to consider:

- Thermal management
- Battery management systems (BMS)
- Charging protocols and limits
- Battery usage (i.e. duty cycles and applications)

[9 marks]

Table Q2

Stage	**C-rate (based on fresh capacity)**	**Duration**
1	-0.4C	15 minutes
2	-0.8C	10 minutes
3	-4.0C	75 seconds
4	0.2C	40 minutes

3. A battery pack is being designed to have an energy of 45 kWh and maximum discharge power of 140 kW. The designer can choose from two potential cells with specification given in Table Q3.

(a) How many cells are required to meet both the energy and power requirements if the battery pack is made from cell A? [2 marks]

(b) How many cells are required to meet both the energy and power requirements if the battery pack is made from cell B? [2 marks]

(c) Which choice of cell will give the lightest pack, and which will give the smallest pack? [3 marks]

(d) If the cost of assembling each cell into a pack is £0.20 per cell, which cell gives the minimum pack cost considering both the cost of cells and pack assembly? [3 marks]

(e) Describe the differences between how a battery pack would be designed for a low-cost application (such as an entry-level electric vehicle) compared to a high-cost, high performance application (such as motorsport or aerospace). In your answer, you may wish to consider:

- Cell selection (i.e. chemistry)
- Pack design
- Thermal management
- Battery management system

[10 marks]

Table Q3

Property	**Cell A**	**Cell B**
Capacity (Ah)	10	60
Energy (Wh)	35	200
Dimensions (l x w x t) (mm)	65 x 100 x 10	270 x 220 x 10
Max discharge rate and voltage under load	4C (3.6 V)	3C (3.7 V)
Mass (g)	150	850
Cost (£)	5.30	31

4. A ‘blade type’ prismatic lithium-ion cell is being designed with a graphite negative electrode and lithium iron phosphate positive electrode. The cell is made from multiple single layers, where each layer consists of a positive electrode foil, negative electrode foil, and two separators. Each electrode foil is coated on both sides with active material, as specified in Table Q4.

(a) What is the negative to positive (N/P) ratio of the cell? [3 marks]

(b) To give an overall capacity of at least 150 Ah, how many complete layers are required if the positive electrode is cycled between 0.10 and 0.95 levels of lithiation? [3 marks]

(c) The positive electrode material is then switched from LFP to the higher voltage and higher energy density lithium manganese iron phosphate (LMFP). To give the same cell energy, the positive electrode thickness is reduced to 100 μm. What should the new negative electrode coating thickness be to maintain the same N/P ratio? [3 marks]

(d) What is the new capacity of the cell using LMFP if the positive electrode lithiation range and number of layers remain the same? [1 mark]

(e) Describe the different factors involved in selecting a potential positive electrode battery material for different applications. What are the advantages and disadvantages of common positive electrode active materials for different applications? In your answer, you may want to consider:

- Energy density
- Power density
- Durability
- Safety
- Economics and ethics

[10 marks]

Continued/…

Q4 Continued/…

Table Q4

Material	Parameter	Value
Graphite	Specific capacity	370 mAh g^{-1}
	Packed Density	1.9 g cm^{-3}
	Porosity	25%
LFP ($LiFePO_4$)	Specific capacity	160 mAh g^{-1}
	Packed Density	2.2 g cm^{-3}
	Porosity	20%
LMFP ($LiMn_xFe_{(1-x)}PO_4$)	Specific capacity	150 mAh g^{-1}
	Packed Density	2.4 g cm^{-3}
	Porosity	22%
-	Negative electrode thickness	70 μm
-	Positive electrode thickness	120 μm
-	Electrode height	300 mm
-	Electrode width	1000 mm

END OF PAPER

A Fly

List of equations

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

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

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

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

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

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

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

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

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 $m\ s^{-2}$