Battery Testing Consortium Protocol

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Round:	1

1 Overview

The Battery Testing Consortium (BTC) has been developed within the High Voltage and Energy Storage Lab at Oxford Brookes University to provide accurate and comprehensive cell data to Formula Student electric teams. Through the BTC, we aim help FS teams have improved and informed decisions for cell selection, pack architecture design, thermal cooling requirements, and end of life predictions. A range of tests are completed to provide a comprehensive electrochemical lithium-ion characterisation for modelling, validation, and battery management parameterisation.

2 Equipment

All testing is completed in an environmental chamber using adequate fixtures to ensure safety of the lab and integrity of the experiment. Testing must be completed on test channels with adequate current and voltage capabilities.

Table 1: Test Equipment

Equipment	Model	Calibration Date
Thermal Chamber 1	Binder KB115	30-03-2021
Thermal Chamber 2	Binder KB115	30-03-2021
Thermal Chamber 3	Binder KB115	01-04-2021
Thermal Chamber 4	Binder KB115	01-04-2021
Thermal Chamber 5	ESPEC PU-4J	29-09-2020
Cell Cycler	ARBIN LBT-21084-HC	23-09-2021
EIS Potentiostat	GAMRY Interface 5000P	N/A

3 Cell Specifications, Test Limitations, & General Test Conditions

Table 2: Rated Cell Specifications

Cell	Chemistry	Nominal Voltage [V]	Initial AC Impedance $m\Omega$	Initial DC Resistance $m\Omega$	Nominal Capacity [Ah]	Energy Density [Wh/kg]	Power Density [W/kg]
Sony VTC6	NMC	3.6	8 - 18	N/A	3	232	4056
LG HG2	NMC	3.6	14 - 16	24 - 26	3	236	1834
Samsung 25R	NMC	3.6	≤ 18	N/A	2.5	206	4325
Melasta SLPBB 042126HV	LCO / NMC	3.8	≤ 1.5	N/A	7.5	228	4176
Melasta SLPB 9542124HV	LCO / NMC	3.8	≤ 1.6	N/A	5.95	215	5593
Melasta SLPBB 142124	LCO	3.7	< 1.6	N/A	6.8	202	4606
Melasta SLPB 8346143	LCO	3.7	1.3±0.3	N/A	6.3	196	4447
Melasta SLPB 7336128HV	LCO / NMC	3.8	< 2.6	N/A	3.7	204	5043
Melasta SLPB 8542126	LCO	3.7	1.6±0.3	N/A	5.2	189	4457
Melasta SLPB 8870175	LCO	3.7	< 1.5	N/A	12	197	4480
Melasta SLPB 6542126	LCO	3.7	≤ 2.3	N/A	3.9	191	5007
Melasta SLPB 7579207HV	LCO / NMC	3.8	1.0±0.2	N/A	15.4	227	3895

3.1 General Test Conditions

3.1.1 Charging Procedure

The manufacturers standard charging procedure as listed in section **??** should be followed throughout the procedure to prevent damaging the cell unintentionally. If a different charging procedure is to be followed, justification should be made.

3.1.2 Temperature Sensing

Thermocouples will be utilised throughout the protocol to sense the cell temperatures. Type-T thermocouples are to be used with data acquisition through the cell cycler. Thermocouples should be placed on the cylindrical and pouch cells as per Figure 1 and 2 below. Thermal paste is applied to the sensing locations with Kapton tape or an equivalent tape covering the thermocouples to ensure consistent surface measurements. The numbering of these channels will be held consistent throughout this protocol. If the data export is missing channel numbers, data was not capture for those locations in the corresponding test. Location 1 should be used at a minimum for both pouch and cylindrical cells with additional thermocouples for high current testing as channels are available.

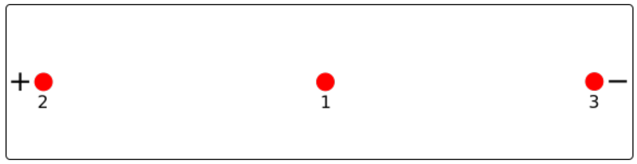

Figure 1: Thermocouple Placement on Cylindrical Cells

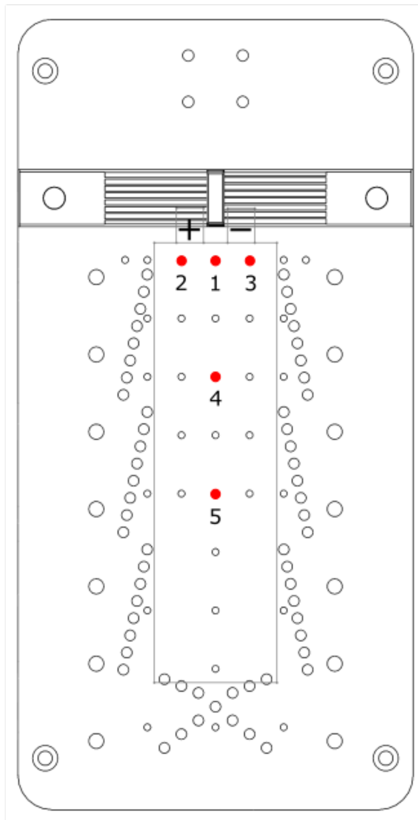

Figure 2: Thermocouple Placement on Pouch Cells

3.2 Pressure Sensing

SingleTact 15 mm diameter, 450 N sensors should be used throughout this experiment. Sensors should be attached to the top plate using Kapton, or an equivalent tape, in the locations shown in Figure 3. At a minimum, locations 1 and 2 should be used with location 3 used if an additional sensor is available.

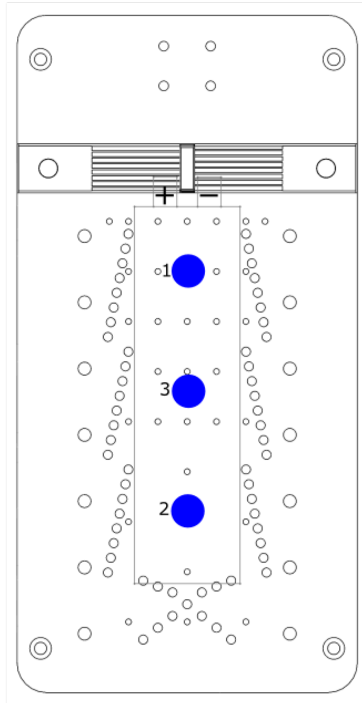

Figure 3: Pressure Sensor Placement on Pouch Cells

4 Overall Protocol

To acquire a full characterisation of the corresponding cells, the individual test definitions were developed and can be found in the subsections below. For all internal resistance measurements throughout this protocol, a current amplitude of 250mA in cylindrical cells and 1C for the relevant pouch cells (i.e. 5A for a 5Ah cell). The frequency used for these internal resistance measurements was 10Hz. For the pouch cells referred to in Table 2, the modular pouch pressure fixture (MBPF) is utilised with a stack pressure of 41.4 kPa unless otherwise specified. For more information on the MBPF please refer to the GitHub repo. The specific protocols can be found in Appendix B-J.

4.1 Cell Conditioning

Each cell is cycled five times at 1C discharge and the standard charge. This test is completed at 25 °C.

4.2 Pseudo-OCV

A discharge and charge of C/25 is completed with a minimum 1 hour rest in between to acquire a pseudo-OCV curve at varying temperatures. Cells 1 and 2 are tested at 5, 15, 25, 35, and 45°C. If the data sheet allows, this test should also be completed at 55°C. Cells 5 and 6 are tested at 25°C to investigate variations across cell samples.

4.3 Galvanostatic Intermittent Titration Technique (GITT)

GITT testing can provide high fidelity OCV determination as well as providing information on the diffusion coefficient at differing states-of-charge. For this experiment an SOC step of 5% will be used with a 3.5-hour rest period between steps. These values are based off of recommendations from Lui et al [1]. Cells 1 and 2 are tested at 5, 15, 25, 35, and 45°C. If the data sheet allows, this test should also be completed at 55°C. Cells 3, 4, 7 and 8 are tested at 25°C to investigate variations across cell samples.

4.4 Hybrid Pulse Power

The hybrid pulse power characterisation test is completed to determine the pulse power capabilities of the cell at various temperatures and pulse rates. Tests are to be completed with the following test conditions and pulses at 5% SOC increments. Figure 4 and table 4 show the pulse profile to be followed. Please note that the current in the plot is relative and should be multiplied by the discharge rate presented in table 3. If the cell does not allow for charge pulses at 75% of discharge rate, then the max allowable charge rate should be used for the charge pulse. Additionally, if voltage limits are reached, the cycler will enforce these limits by clamping current.

Table 3: Temperature and Discharge Rates for HPPC

Temperature	Discharge Rates
5°C	$D_{max}/2$ D_{max}
15°C	$D_{max}/2$ D_{max}
25°C	$D_{max}/2$ D_{max}
35°C	$D_{max}/2$ D_{max}
45°C	$D_{max}/2$ D_{max}

Table 4: HPPC Pulse Profile

Time Increment (s)	Cumulative Time (s)	Relative Current
10	10	-1.00
40	50	0
10	60	0.75
40	100	0

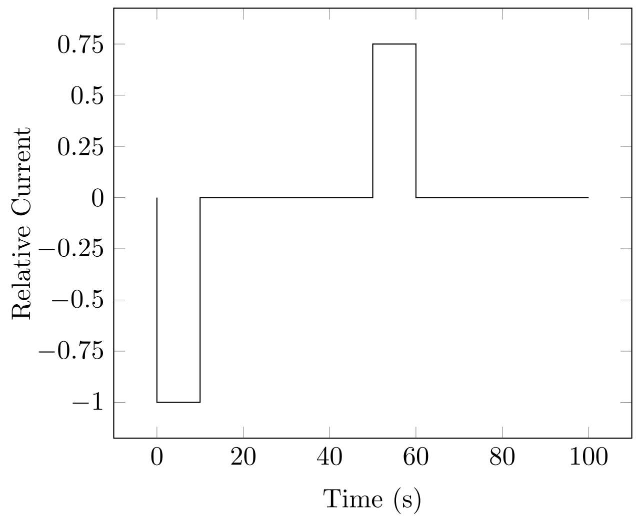

Figure 4: HPPC Pulse Profile

4.5 Electrochemical Impedance Spectroscopy (EIS)

A potentiostat or galvanostat EIS test is to be performed from 1mHz to 1kHz with 5% SOC increments and 8 points per decade. This test is completed at 5, 15, 25, 35, and 45°C with a current amplitude of 250mA for cylindrical cells and 5mV RMS voltage amplitude for pouch cells. It is recommended that this test be performed in conjunction of the HPPC test to reduce testing time.

4.6 Constant Current Capacity

Static capacity tests are completed at a variety of discharge rates and temperatures to determine discharge efficiencies, and expected capacities. Table 5 below shows the conditions at which the tests will be completed. Charging should follow standard charging procedures.

Table 5: Temperature and Discharge Rate for Capacity Testing

Temperature	Discharge Rates
5°C	$D_{max}/5$ $2D_{max}/5$ $3D_{max}/5$ $4D_{max}/5$ D_{max}
15°C	$D_{max}/5$ $2D_{max}/5$ $3D_{max}/5$ $4D_{max}/5$ D_{max}
25°C	$D_{max}/5$ $2D_{max}/5$ $3D_{max}/5$ $4D_{max}/5$ D_{max}
35°C	$D_{max}/5$ $2D_{max}/5$ $3D_{max}/5$ $4D_{max}/5$ D_{max}
45°C	$D_{max}/5$ $2D_{max}/5$ $3D_{max}/5$ $4D_{max}/5$ D_{max}

4.7 Cycle Degradation

Three cells undergo degradation cycles to capture expected lifetime under various conditions. Drive cycles have been chosen to capture various stresses that are relevant to Formula Student competitions.

Cell 5 is cycled at constant pack discharge power of 15kW for a time equivalent to half the simulated endurance followed by a 3 minutes rest before repeating the 15kW discharge. This is then followed by a 30 minute rest and charged using the standard charge procedure. This cell aims to capture capacity throughput degradation with the selected power chosen from a statistical analysis of previous published Formula Student results. This discharge is scaled by the 600V pack architecture for each cell shown in Appendix A below.

Cell 6 performs an endurance drive cycle that includes 22 laps with a 3 minute rest halfway through, followed by a 30 minute rest and then a standard charge. The endurance drive cycle, as shown in the figure below, has been created using AVL VSM, and is representative of the 2017 MIS endurance course for a 4WD, 200kg electric vehicle. Additional information on this cycle can be viewed in the resources folder. This cycle is scaled by the pack architectures for each cell shown in Appendix A below, with this test completing the 600V section.

Cell 7 performs the same cycle as cell 6, except with the 450V pack architecture.

Ambient temperature for this section is 30°C, with cycling continuing until end of life (EOL), defined as 80% of initial capacity, is achieved or 200 cycles have been completed. Every ten cycles a reference performance is completed including an EIS test as per section 4.5, internal resistance, and a static capacity at standard charge and C/2 discharge. A pseudo-OCV curve is acquired every 40 cycles in addition to the 10-cycle RPT. If resources are available, additional thermal characterisation is performed.

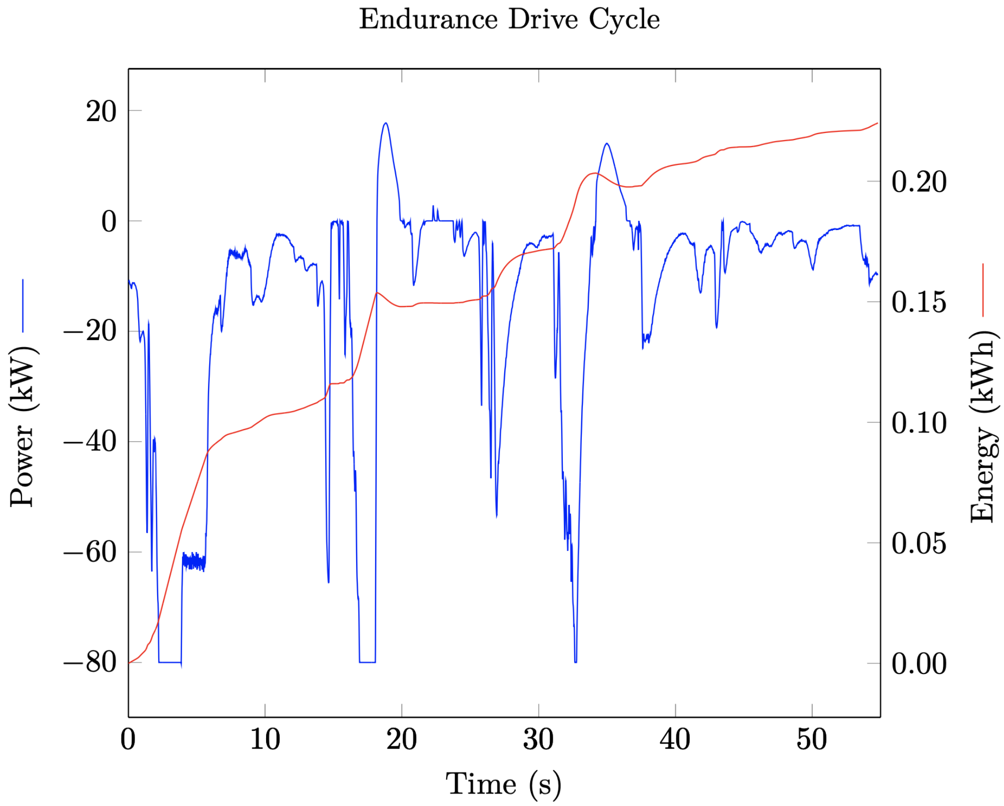

Figure 5: Endurance Drive Cycle - Power and Used Energy vs. Time

4.8 Calendar Ageing

This test investigates the effects of storage temperature on cell ageing. If available, cells 9-12 are stored in climate controlled environments with a reference performance test completed every 2 months. Cells 9-10 are stored at 15°C with cells 11-12 stored at 30°C.

4.9 Pressure-Degradation Investigation

This test aims to investigate stack pressure variation during cycle ageing. Available pouch cells are pressurised via the Modular Battery Pressure Fixture and cycled via the 600V drive cycle section 4.7 with an EIS RPT completed every 10 cycles. This RPT will include a potentiostatic EIS test from 1mHz to 1kHz with 8 points per decade, an internal resistance test, and a capacity test. The EIS and internal resistance tests will be completed with a stack pressure of 40, 80, 120, and 160 kPa. The pressure that produces the lowest average DC resistance will be used for the next range of cycles until another RPT is preformed. Ambient temperature for this section is 25°C, with cycling continuing until end of life (EOL), defined as 80% of initial capacity, is achieved or 200 cycles have been completed.

5 References

[1] A. Barai et al., ‘A comparison of methodologies for the non-invasive characterisation of commercial Li-ion cells’, Progress in Energy and Combustion Science, vol. 72, pp. 1–31, May 2019, doi: 10.1016/j.pecs.2019.01.001.

Appendix A - Model and Cell Test Distribution

Cells	Test 4.1	Test 4.2	Test 4.3	Test 4.4	Test 4.5	Test 4.6	Test 4.7	Test 4.8	Test 4.9
1-2	X	X	X	X	X				
3-4	X		X			X			
5-6	X	X					X		
7	X		X				X		
8	X		X						X
9-12	X	X						X	

Cell Type	Cell Identifier	Test Group ID
Sony VTC6	10-0002	1
	10-0003	2
	10-0004	3
	10-0005	4
	10-0006	5
	10-0007	6
	10-0008	7
	10-0009	8
	10-0010	9
	10-0011	10
	10-0012	11
	10-0013	12

Cell Type	Cell Identifier	Test Group ID
Samsung 25R	10-0053	1
	10-0054	2
	10-0055	3
	10-0056	4
	10-0060	5
	10-0066	6
	10-0058	7
	10-0065	8
	10-0061	9
	10-0062	10
	10-0063	11
	10-0064	12

Cell Type	Cell Identifier	Test Group ID
LG HG2	10-0073	1
	10-0074	2
	10-0075	3
	10-0076	4
	10-0077	5
	10-0078	6
	10-0079	7
	10-0080	8
	10-0081	9
	10-0082	10
	10-0083	11
	10-0084	12

Cell Type	Cell Identifier	Test Group ID
SLPB8542126	11-0001	1
	11-0002	2
	11-0003	3
	11-0004	4
	11-0005	5
	11-0006	6
	11-0007	7
	11-0008	8

Cell Type	Cell Identifier	Test Group ID
SLPBB043236HV	11-0009	1
	11-0010	2
	11-0011	3
	11-0012	4
	11-0013	5
	11-0014	6
	11-0015	7
	11-0016	8

Cell Type	Cell Identifier	Test Group ID
SLPB8346143	11-0017	1
	11-0018	2
	11-0019	3
	11-0020	4
	11-0021	5
	11-0022	6
	11-0023	7
	11-0024	8

Cell Type	Cell Identifier	Test Group ID
SLPB6542126	11-0025	1
	11-0026	2
	11-0027	3
	11-0028	4
	11-0029	5
	11-0030	6
	11-0031	7
	11-0032	8

Cell Type	Cell Identifier	Test Group ID
SLPBB142124	11-0033	1
	11-0034	2
	11-0035	3
	11-0036	4
	11-0037	5
	11-0038	6
	11-0039	7
	11-0040	8

Cell Type	Cell Identifier	Test Group ID
SLPB7336128HV	11-0041	1
	11-0042	2
	11-0043	3
	11-0044	4
	11-0045	5
	11-0046	6
	11-0047	7
	11-0048	8

Cell Type	Cell Identifier	Test Group ID
SLPB9542124HV	11-0049	1
	11-0050	2
	11-0051	3
	11-0052	4
	11-0053	5
	11-0054	6
	11-0055	7
	11-0056	8

Cell Type	Cell Identifier	Test Group ID
SLPB8870175	11-0057	1
	11-0058	2
	11-0059	3
	11-0060	4
	11-0061	5
	11-0062	6
	11-0063	7
	11-0064	8
	11-0065	9
	11-0066	10
	11-0067	11
	11-0068	12

Cell Type	Cell Identifier	Test Group ID
SLPB7579207HV	11-0069	1
	11-0070	2
	11-0071	3
	11-0072	4
	11-0073	5
	11-0074	6
	11-0075	7
	11-0076	8
	11-0077	9
	11-0078	10
	11-0079	11
	11-0080	12