Battery Testing Consortium: A Framework for Improvements in High-Power Battery Design

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Background

The Battery Testing Consortium aims to quantify and analyse high-power cells for usage in Formula Student applications. This project provides the largest engineering competition community with insight into electrochemical degradation mechanisms, thermal properties and their corresponding design requirements, usable energy and power densities, and calibration data for battery management systems. This is completed through a variety of experimental standards that provide a diverse and comprehensive data set.

Motorsport and high-performance automotive applications are currently challenged by the "AND" problem, as key benefits can be found with a couple high energy "AND" power cell. Due to constraints in current chemistries, this problem is classically solved through shortening of usable cycle life, or in more traditional automotive applications, de-rating the battery power output. To provide further insight on improvements in the problem, the battery testing consortium provides a benchmark for current chemistries. This project experimentally tests a variety of available for purchase cells in a harsh, prolonged testing regime.

Key challenges and outcomes for this work include capturing cell-to-cell variation while minimising testing resources as well as, data management and efficient methods for dissemination. Additionally, for the pouch cells, determining pressure requirements and ensuring application accurate testing. Further work towards optimal pressure fixturing is planned, with Figure 1 showcasing the constant displacement method utilised.

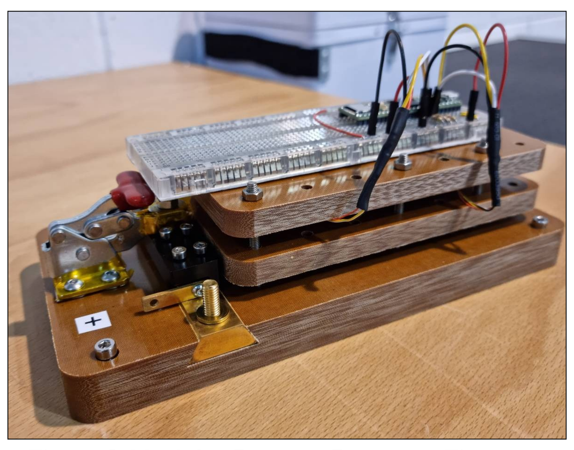

Figure 1: Modular Battery Pressure Fixture

Methodology

Figure 2 showcases the test selection for this project, for the eight cells used per model. These tests have been selected to provide the maximum amount of information for a given cells.
The Galvantic intermitent titration test (GITT) is completed for six cells, with a Pseudo-OCV completed for four. A hybrid pulse power characterisation test is completed on two cells with EIS completed in parallel. This test is preformed at five different temperatures shown in Table 1.

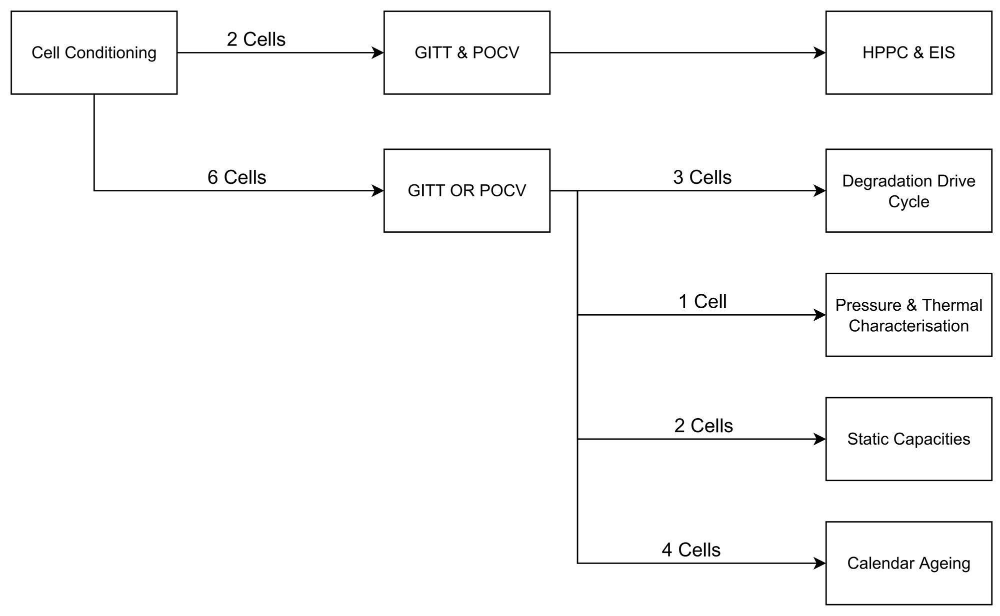

Figure 2: Cell Characterisation Flowchart

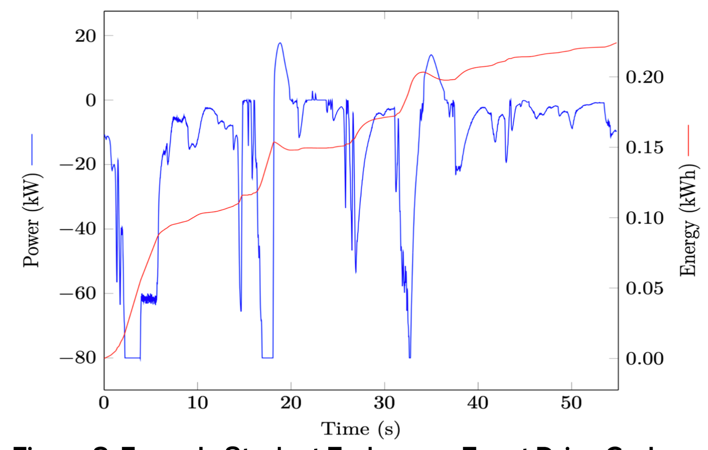

Figure 3: Formula Student Endurance Event Drive Cycle

Degradation cycling is completed for three cells, configured for two pack architectures (450V & 600V) while minimising the variance in pack energy. Two of the cells are cycled for 200 cycles or 80% SOH with the drive-cycle shown in Figure 3. The remaining cell completes a repeated static 15kW discharge.

Table 1: Temperatures Ranges

Test	Temperature(s)
Cell Conditioning	25°C
POCV & GITT	5-55°C
HPPC & EIS	5-55°C
GITT or POCV	25°C
Degradation Drive Cycle	30°C
Calendar Aging	15°C or Ambient
Static Capacity	5-55°C

Static capacity testing is completed for two cells at five temperatures and five current rates [Table 2]. Calendar ageing is also completed for each chemistry utilised, with two cells stored at 15°C and additional two stored at ambient temperature.
Finally, thermal characterisation and pressure investigations are performed with the final cell. This involves degrading the cell to 80% state-of-health while exploring optimal pressure. A thermal characterisation is added to the reference performance test every 10 cycles. For cylindrical cells, only the initial thermal characterisation is performed.

Cell Selection / Variation

A total of twelve cells have been selected for this project, with selection based on both popular models and a cost function optimisation.

Table 2 showns cell-to-cell variations for the selected cells. As expected, the pouch cells have a higher cell variation but achieve excellent internal resistance values.

Table 2: Cell-to-Cell Measured Values

Cell	Chemistry	Internal Resistance [mΩ]	Capacity [Ah]	Mass [g]
Sony VTC6	NMC	18.3 - 21.1	3.0 - 3.1	46.5 - 46.9
LG HG2	NMC	20.1 - 21.1	2.9 - 3.0	43.6 - 43.8
Samsung 25R	NMC	16.5 - 17.9	2.5 - 2.5	45.9 - 46.1
Melasta SLPBB042126HV	LCO/NMC	5.7 - 6.6	7.5 - 7.7	126.0 - 127.0
Melasta SLPB9542124HV	LCO/NMC	3.6 - 4.1	6.0 - 6.4	104.8 - 105.9
Melasta SLPBB142124	LCO	2.9 - 3.0	6.8 - 7.2	122.1 - 122.6
Melasta SLPB8346143	LCO	3.1 - 3.3	6.4 - 6.6	114.3 - 114.9
Melasta SLPB7336128HV	LCO/NMC	11.6 - 12.5	3.8 - 4.0	65.7 - 66.2
Melasta SLPB8542126	LCO	3.5 - 3.8	5.3 - 5.5	95.5 - 96.4
Melasta SLPB8870175	LCO	1.7 - 2.3	12.3 - 12.9	222.9 - 223.8
Melasta SLPB6542126	LCO	4.5 - 5.1	4.0 - 4.2	73.2 - 73.9
Melasta SLPB7579207HV	LCO/NMC	2.9 - 3.9	15.1 - 16.0	258.0 - 261.7

Battery Management

Alongside providing optimal cell selection information, the BTC provides a variety of parameters that can inform both battery management systems and the partnering control structures. As mentioned above, open circuit voltage is obtained through both pseudo OCV testing and GITT methods. This data is obtained at different temperatures for each cell [Figure 4]. While at a glance, the plot seems fairly consistent for states-of-charge above 25%, it can be seen in Figure 5, that there is an SOC variation of two percent at 3.8V for the tested tempatures. This data allows for OCV curves to be predicte at multiple operating temperatures, providing improved state estimations.

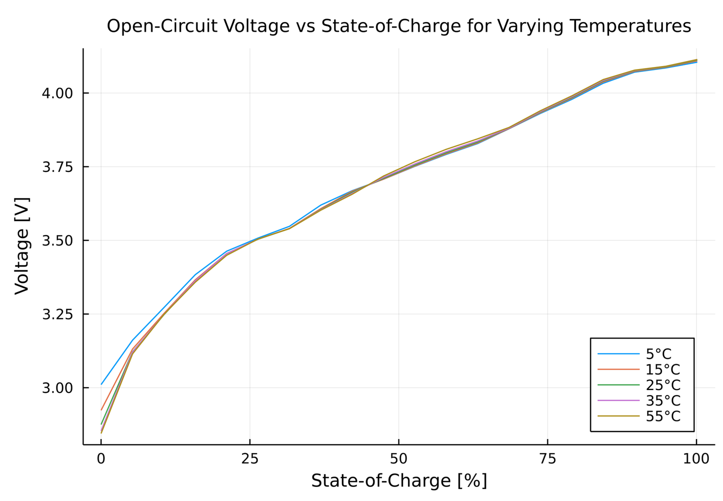

Figure 4: Open Circuit Voltage for a Sony VTC6

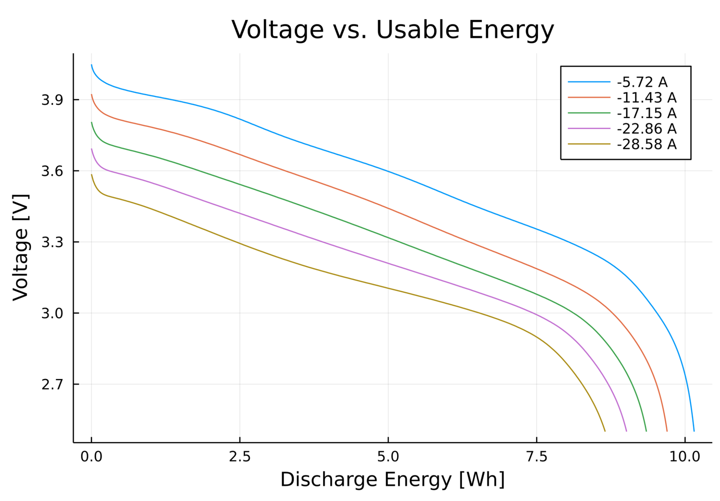

Figure 6: Open Circuit Voltage for a Sony VTC6 at 3.8V

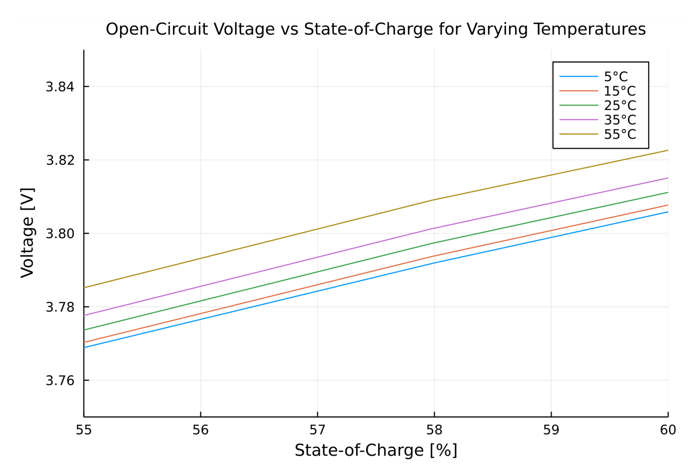

Figure 5: Open Circuit Voltage for a Sony VTC6 at 3.8V

Additionally, usable energy can be obtained through static capacity testing for various discharge rates, allowing for control optimisation for different Formula Student events [Figure 6]. Finally, resistance data is obtained both through classical methods [Figure 7] and electrochemical impedance spectroscopy testing at a variety of frequencies [Figure 8]. This data is beneficial for BMS optimisation and thermal management design.

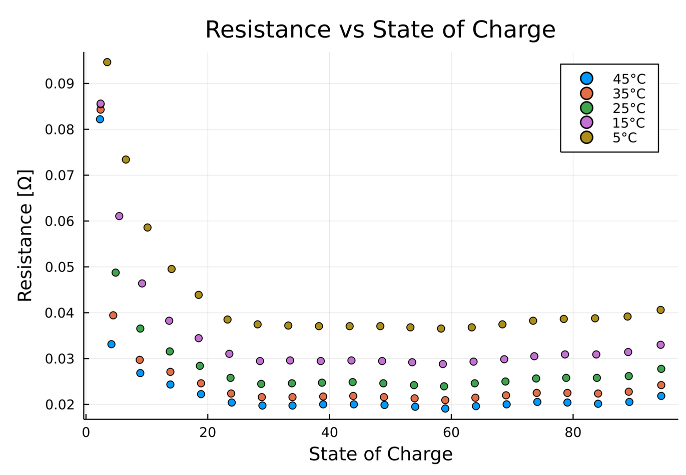

Figure 7: Resistance vs State of Charge for a Sony VTC6

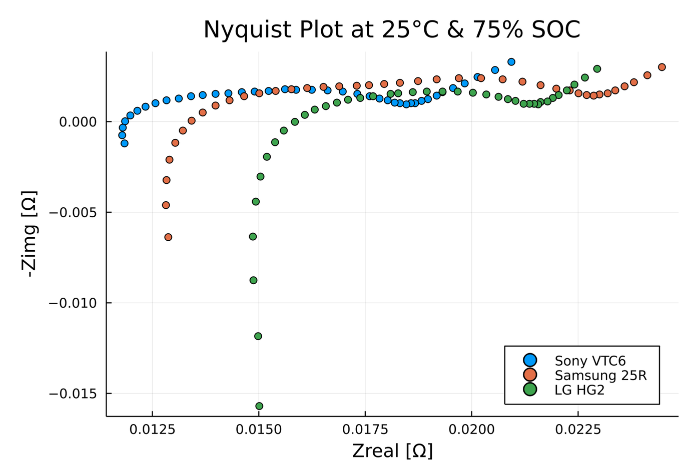

Figure 8: Impedance Data for Various Cells

Degradation

Obtaining long-term degradation data can provide a wealth of critical information, including but not limited to capacity fade, resistance growth, and state-of-health. For this work, it was important to get relevant operational data, thus a high power drive-cycle was created to represent a Formula Student endurance lap [Figure 3]. This drive cycle is run 22 times to form a the total event. Lastly, this is repeated 200 times or until state-of-health reached 80%, measured every 10 cycles.

Pack configurations were selected to represent the required energy and voltage targets. Table 3 shows the final configurations for two pack voltage targets. An addition cell was tested at a 15kW constant discharge, capturinf the mean discharge rate for this event.

The result of single event is shown in Figure 9 below. This compares the two cell geometries selected, and is shown as an illistration of the large variation between two similiary size pack configurations.

Table 3: Pack Architecture for Power Cycle

Cell	600V	450V
Sony VTC6	142s4p	107s5p
LG HG2	142s4p	107s5p
Samsung 25R	142s5p	107s6p
Melasta SLPBB042126HV	137s2p	103s2p
Melasta SLPB9542124HV	137s2p	103s3p
Melasta SLPBB142124	142s2p	107s2p
Melasta SLPB8346143	142s2p	107s3p
Melasta SLPB7336128HV	137s3p	103s4p
Melasta SLPB8542126	142s2p	107s3p
Melasta SLPB8870175	142s1p	107s1p
Melasta SLPB6542126	142s3p	107s4p
Melasta SLPB7579207HV	137s1p	103s1p

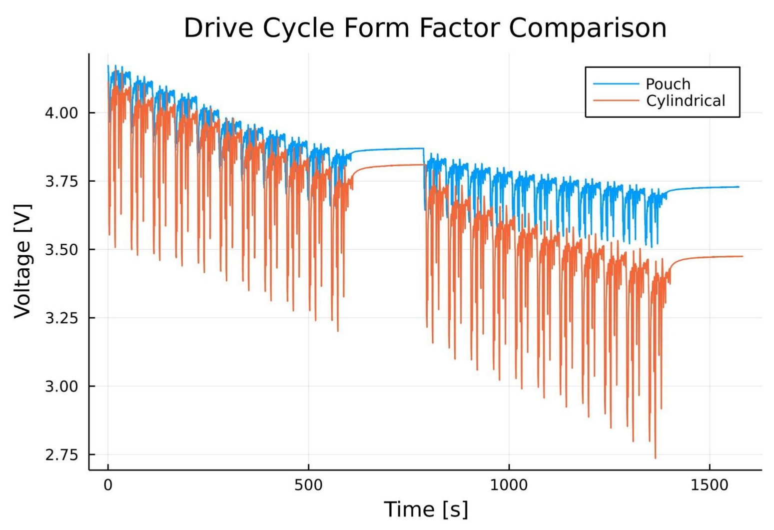

Figure 9: Capacity Fade Comparison

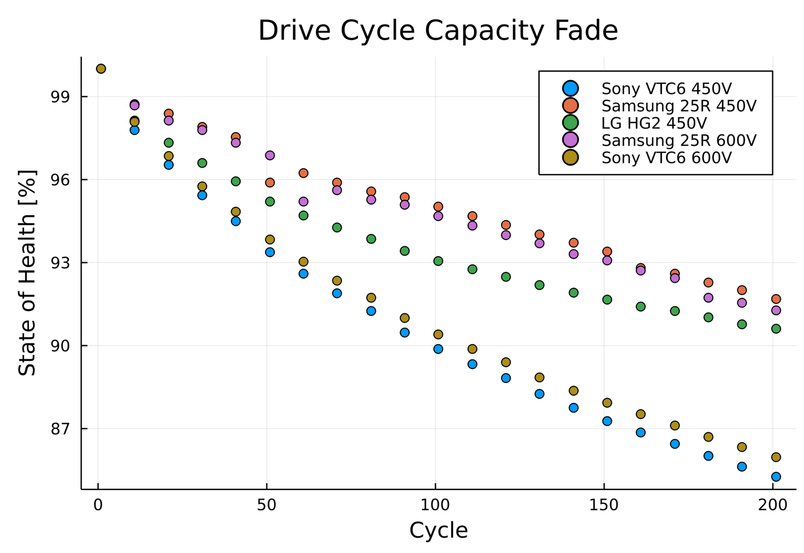

Figure 10: Capacity Fade Comparison

Capacity fade is shown in Figure 10. This provides a comparison between three cells in different pack configurations. This number of cycles is seen as EOL due to vehicle advancements and knowledge retention difficulties. This plot showcases the harsh conditions of this application.

Resistance growth is another parameter provide via drive cycle degradation testing [Figure 12]. This information is beneficial not just for battery management systems as mentioned previously but also provides insight into necessary thermal management solutions. As can be seen in Table 4, while the Samsung 25R has the lowest initial resistance, the growth is over twice that of the LG HG2. This allows for a futher optimised cooling solution across the pack life.

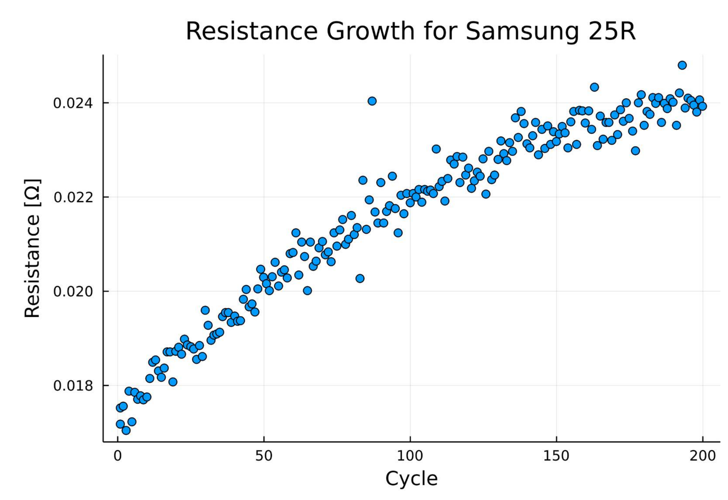

Figure 12: Resistance Growth for a Samsung 25R 450V Pack

Table 4:Resistance Growth over 200 Cycles

Cell Model / Pack Architecture	Average [Ω]	Cycle 0 [Ω]	Cycle 100 [Ω]	Cycle 200 [Ω]	Growth	State-of-Health @ 200 Cycles
Samsung 25R 600V	0.021	0.017	0.022	0.024	41%	91.3%
Samsung 25R 450V	0.022	0.018	0.022	0.024	37%	91.7%
LG HG2 450V	0.022	0.02	0.023	0.023	15%	90.6%
Sony VTC6 600V	0.024	0.019	0.024	0.027	38%	85.9%
Sony VTC6 450V	0.023	0.019	0.024	0.026	37%	85.2%

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http://github.com/Oxford-Brookes-HVES/BTC