Summary of 3rd party testing of SES hybrid lithium-metal cells

Compiled by Dr. Billy Wu and Mark Newman for Ivanhoe Capital Acquisition Corp.

Executive summary

SES is a manufacturer of next generation hybrid lithium-metal batteries with demonstrated multi-layer and multi-Ah cells. In this report, two independent 3rd party test houses (Exponent and Eclipse Energy) have validated the performance claims made by SES. Tests of their 4.2 Ah cells at a range of temperatures (0°C, 25°C and 40°C) and C-rates (0.1-7C) show excellent agreement between the two test houses. An impressive and class-leading nominal energy density of ~370 Wh/kg (0.1C/25°C) has been demonstrated, with exceptional power capability up to 7C (29.4A) whilst retaining > 76% of the nominal energy density even at harsh conditions of 0°C and 7C discharge. Furthermore, fast charging capability at 4C (16.8A) was demonstrated from 10%-80% within 10.5 minutes, showcasing practical real-world performance.

3rd party safety tests (external short circuiting, overcharging and nail penetration) were performed with the SES's cells consistently passing all tests. Accelerating rate calorimetry tests indicate that SES's electrolyte does not react aggressively with molten lithium, further highlighting good safety characteristics.

Overall, the 3rd party testing results confirm SES's leading performance claims with all data clearly presented in this report for full transparency.[1]

In addition, independent 3rd party expert analysis from Professor Shirley Meng validates SES's hybrid lithium metal technology as the leading contender amongst all other known lithium metal battery technologies, with leading energy density, superior cycling life, low temperature performance and rate capability compared to all other known approaches (including solid state electrolytes).[2]

Figure 1: SES 4.2 Ah multi-layer hybrid lithium metal batteries.

[1] Full third-party test house reports are also available.
[2] For more details on Shirley Meng's analysis and opinion, see separate report.

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1. Introduction

SES is a developer of hybrid lithium-metal batteries with the potential to achieve an energy density >400 Wh/kg and 1,000 Wh/L which would represent best-in-class performance. The aim of this document is to summarise the 3rd party testing results performed on SES's cells which was commissioned by Ivanhoe Capital Acquisition Corp.

The two test houses selected were Exponent and Eclipse Energy; both of whom have extensive technical experience and track record in battery testing. Exponent is a publicly listed (NASDAQ:EXPO) multi-disciplinary engineering and scientific consulting firm that brings together more than 90 different disciplines to solve engineering, science, regulatory, and business issues. Eclipse Energy are an Indiana (US) based battery test house with extensive experience and facilities which provides a 2nd layer of validation to Exponent's testing.

In both cases the testing procedures were provided by SES (Appendix 3 and 4), which are inline with standard battery testing procedures. For the electrical cell testing, fixtures (Figure 2) were provided by SES in order to maintain pressure on the cells. Six 4.2 Ah SES hybrid lithium-metal cells were tested at 0°C, 25°C and 40°C with a C-rate ranging from 0.1-7 C which represents a current of 0.42-29.4 A. Each cell had a weight between 43.4-43.6 g with 3 cells tested at each test house. One cell from each batch was also tested for fast charging capability at 4C (16.8 A), 25°C from 10% to 80% state-of-charge.

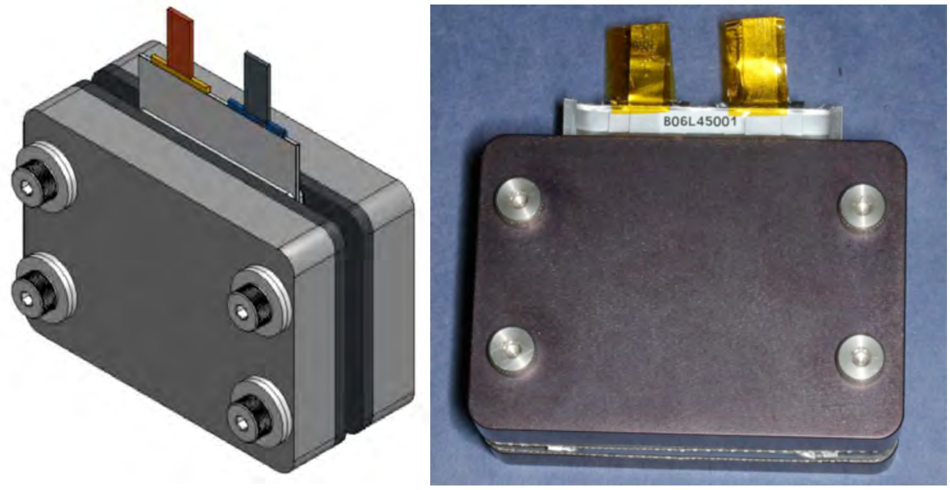

Figure 2: SES cell testing fixture.

2. Highlights of electrical testing results

Both Exponent and Eclipse Energy have produced comprehensive testing reports summarising their 3rd party testing results of the 4.2 Ah SES hybrid lithium-metal cells. Full details of this can be found in their retrospective reports [1,2] but the key findings are summarised here with notable data shown in the appendix.

- An impressive nominal energy density of ~370 Wh/kg at 0.1 C (0.42 A) and 25 ˚C.
- Discharge C-rates up to 7C (29.4 A) with an energy retention >86% at 25 ˚C demonstrating excellent power capabilities.
- Retention of performance at low temperatures (0 ˚C) with 76-88% of the nominal (25 ˚C) capacity accessible (282-328 Wh/kg).
- Excellent consistency of performance between cells, exemplified by agreement of results between 2 independent 3rd party test houses.
- Demonstrated fast charging at 4C (16.8 A) from 10%-80% state-of-charge within 10.5 minutes.

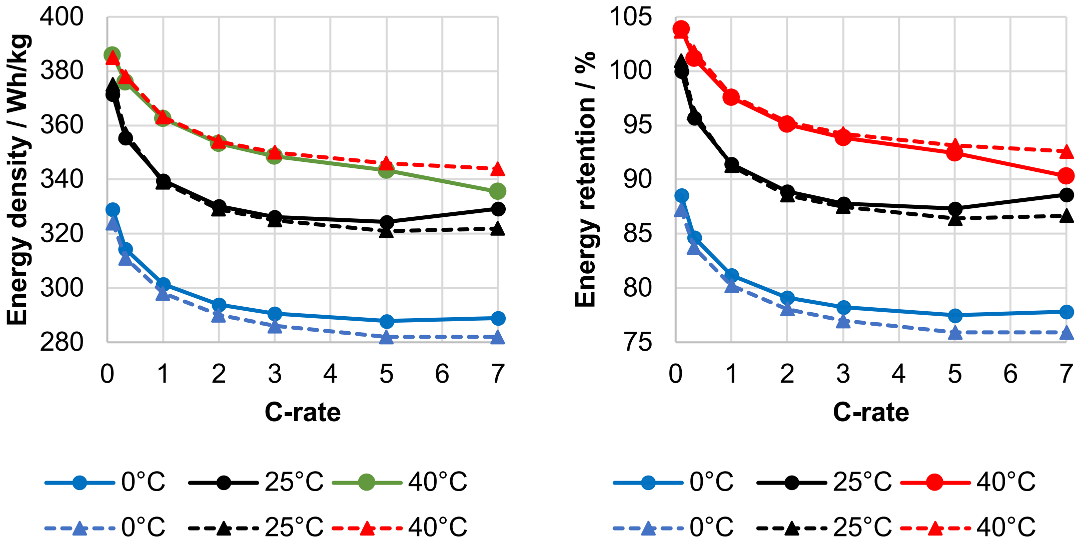

Figure 3: Energy density and energy retention (relative to 0.1C at 25 ˚C) of the SES cells at different temperatures and C-rates. Tested at Exponent (solid lines) and Eclipse Energy (dotted lines).

3. Highlights of safety tests

In order to validate the safety performance of SES's hybrid lithium-metal cells, Exponent was commissioned by SES in 2020 to conduct a series of abuse tests which included: external short-circuiting, overcharge, nail penetration and accelerating rate calorimetry (ARC) tests. In all cases, abuse testing was performed with a charged multi-layer cell with each held within a compression fixture. Use of full large multi-layer cells more accurately represent real-world safety performance than separate testing of each individual component.

Notable results and details of the test set-up are shown in Appendix 5-8 with key conclusions being:

- None of the cells experienced thermal runaway, fire and/or explosion when tested under external short-circuiting, overcharge and nail penetration tests, showcasing good and consistent safety performance.
- ARC tests indicate that SES's electrolyte exhibits limited self-heating when in contact with molten lithium suggesting good safety characteristics.
- While thermal runaway does occur at approx. 324 °C this is attributed to the use of the high-nickel cathode which is the same as other equivalent high energy batteries using nickel rich cathodes.

4. Conclusions

Overall, two independent 3rd party test houses (Exponent and Eclipse Energy) have validated the performance claims of the SES 4.2 Ah multi-layer hybrid lithium-metal batteries. Testing was performed over a range of temperatures (0°C, 25°C and 40°C) and C-rates (0.1-7C) with consistent performance between the two. An excellent nominal energy density of ~370 Wh/kg has been demonstrated as well as exceptional power capability of up to 7C whilst retaining > 76% of nominal energy in all cases. Fast charging capability was also validated at 4C from 10-80% in 10.5 mins. Furthermore, safety tests including: external short-circuiting, overcharge and nail penetration tests were performed with the SES cells consistently passing. ARC tests also indicate that upon heating cells externally, SES's electrolyte exhibits limited self-heating when in contact with molten lithium, indicting good thermal stability.

Author profiles

Dr. Billy Wu

Dr. Billy Wu is a senior lecturer (associate professor) in electrochemical engineering at Imperial College London, UK. He co-leads the Electrochemical Science and Engineering group which works at the interface between fundamental science and engineering application of electrochemical energy storage/conversion devices such as batteries, fuel cells and supercapacitors. Cross cutting activities include: energy materials, continuum modelling, diagnostic/characterisation techniques, thermal management system, control and techno-economics. He has published >50 peer reviewed papers in leading scientific journals and sits on the editorial board of Scientific Reports, Energy & AI, HardwareX and the Journal of Power and Energy. He manages a multi-million pound research portfolio of industry/research council projects and is part of the UK Faraday Institution's multi-scale battery modelling project.

Mark Newman

Mark Newman is Chief Commercial Officer (CCO) and Head of Strategy for Nyobolt, the original founders of ultra-fast charging niobium-based battery technology. Mark is also a frequent speaker and commentator on batteries, electric vehicles and semiconductors. He is an investor, and advisor to both investors and start-ups as well as serving on the Board of the Faraday Institution.

Mark previously spent 11 years as Managing Director and Senior Analyst covering Technology at Bernstein, where he was lead author of numerous Bernstein Blackbooks including "The Battery Bible", "Electric Revolution" (2017, 2018, 2019 and 2020 editions), and "The New Memory Paradigm". Mark's research at Bernstein focused on batteries, electric vehicles and semiconductors.

Prior to Bernstein, Mark worked at Samsung in Korea for six years, during which time he held various strategy and business development roles, most recently as Director of Strategic Planning in Samsung's Semiconductor Business. At Samsung, Mark was a key driver of several strategic initiatives, venture investments and acquisitions.

Before Samsung, Mark spent four years working in Field Operations at Applied Materials in California, where he supported the world's leading semiconductor manufacturing companies in the United States, Europe and Asia. He also worked at Singapore Technologies in Singapore and Aker Kvaerner in New Jersey. Mark earned a Master's in Chemical Engineering from University College London, and an MBA from Harvard Business School.

Appendix 1 – Exponent testing data

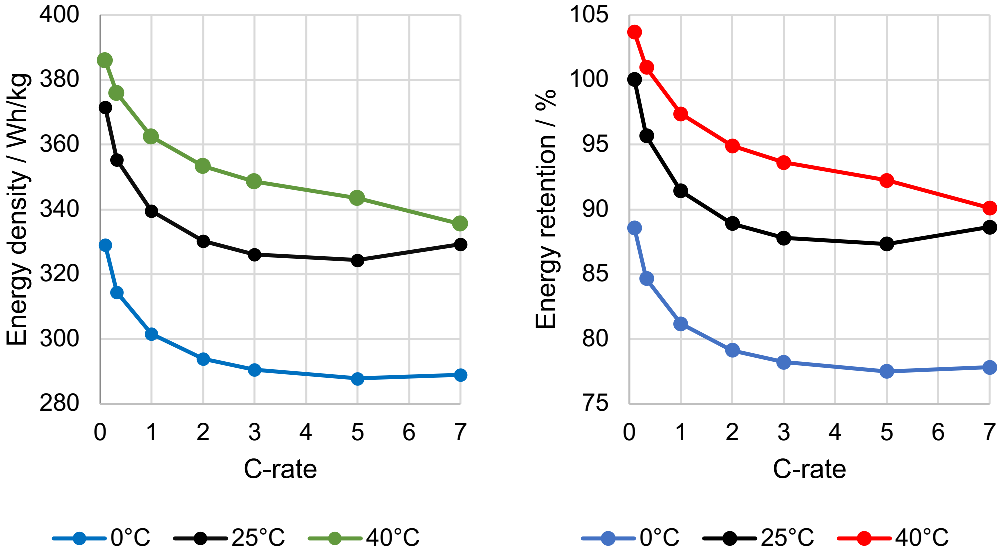

Figure 4: Energy density and energy retention (relative to 0.1C at 25 ˚C) of the SES cells at different temperatures and C-rates. Tested at Exponent.

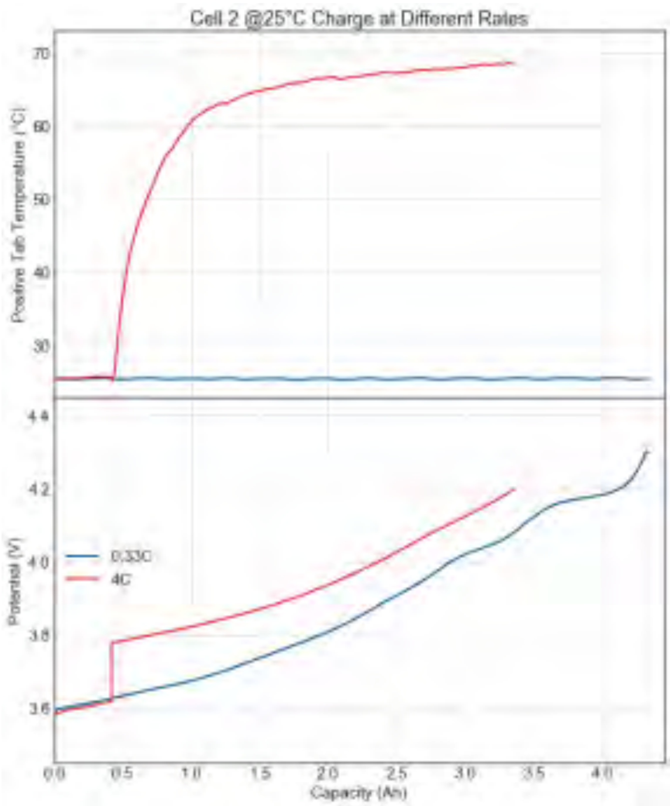

Figure 5: Fast charging data for the SES cells at 25 ̊C from 10%-80% state-of-charge at 4C taking 10.5 mins. Tested at Exponent.[3]

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[3] Note that the fast-charging tests were done from 10%-80% state-of-charge according to the procedure in Appendix 4 which is more representative of real-world use cases. The 0.33C charge voltage shows the slow charge voltage profile. In the fast charge case, a 0.33C charge current is used from 0% to 10% state-of-charge and then switched to 4C up to 80% state-of-charge (3.36 Ah total throughput with a 2.94 Ah throughput for fast charging). The fast charging thus represents a 10-80% charge time of 10.5 minutes as the upper cell voltage limit of 4.3 V was not hit.

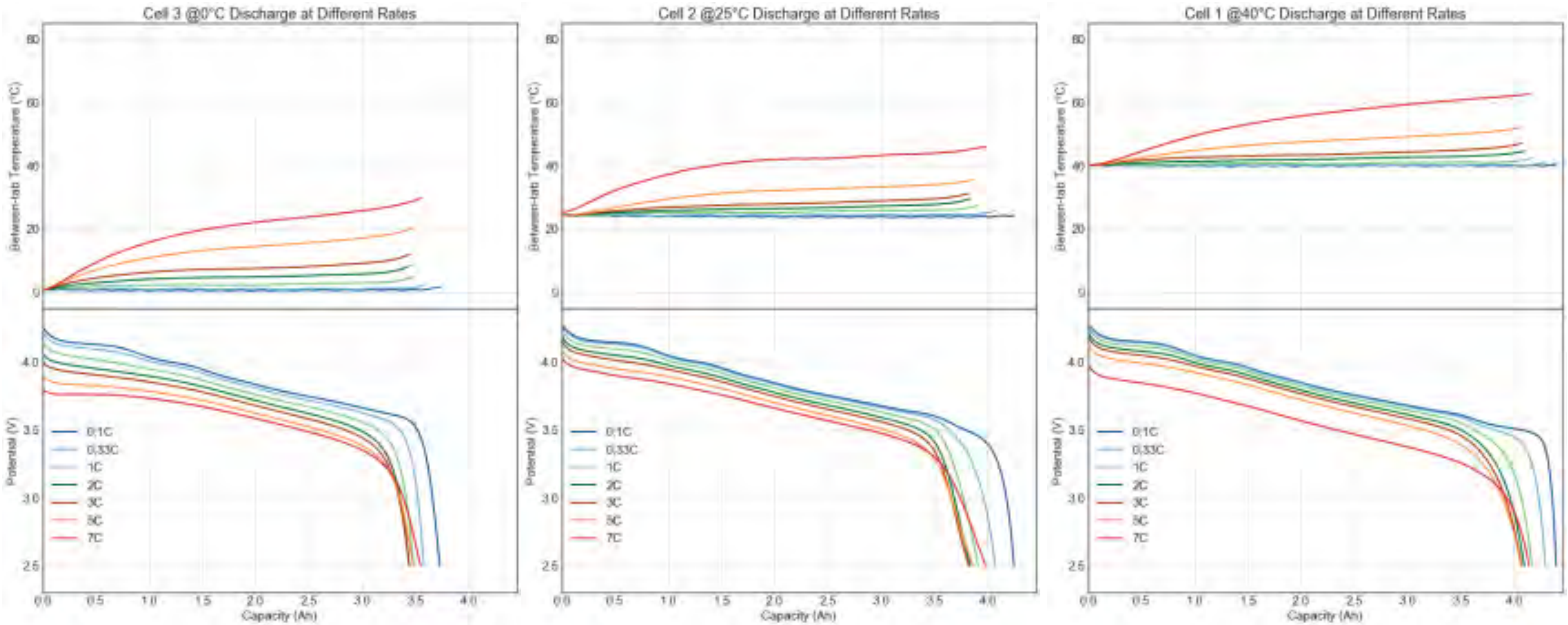

Figure 6: Voltage and temperature profiles for SES cells tested at 0˚C, 25 ˚C and 45 ˚C, grouped by temperature. Tested at Exponent.[4]

[4] Note that the temperature plotted is at the top centre of the cell which is more representative of the intrinsic cell heat generation. Whilst it is acknowledged that the peak temperature is at the positive aluminium tab due to the additional heat generation from the tab contact, this can easily be optimised to reduce peak temperature. Furthermore, no active thermal management of these cells were applied.

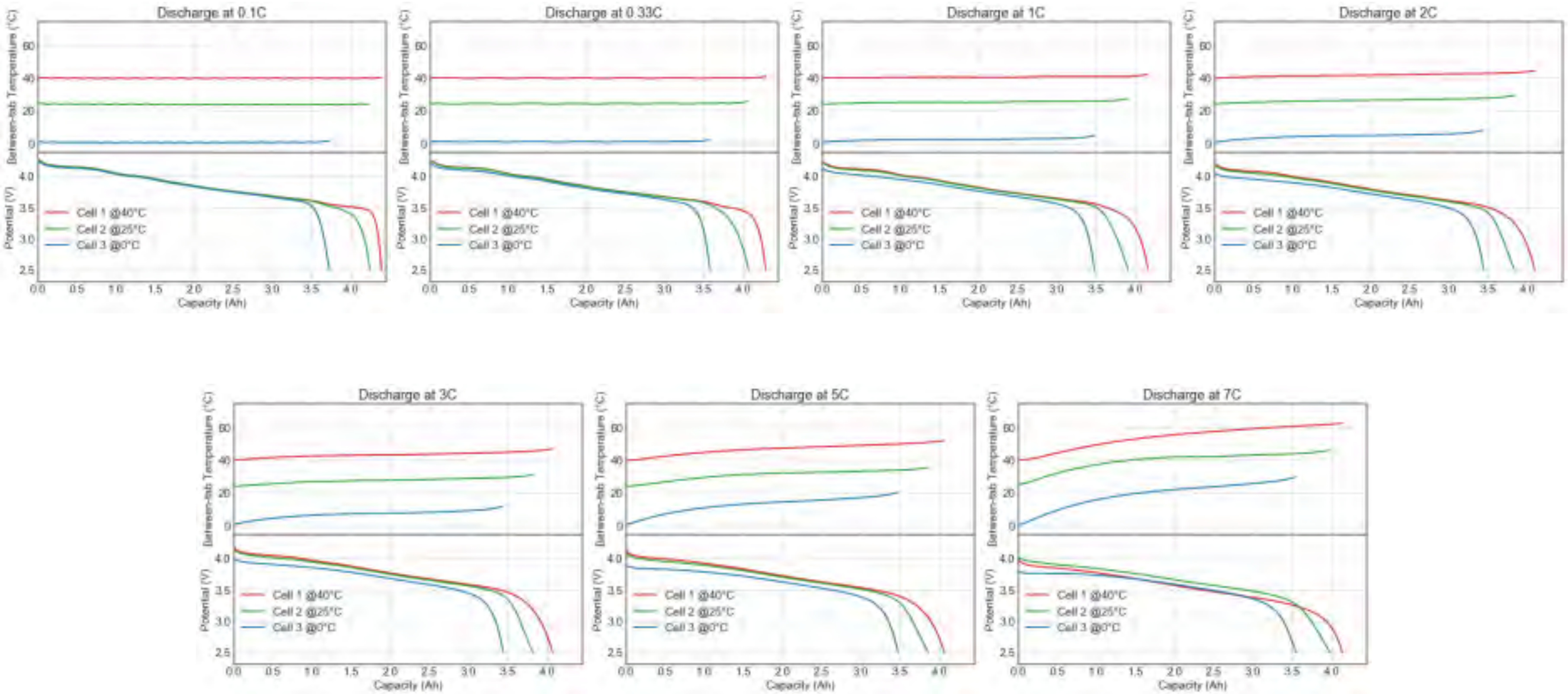

Figure 7: Voltage and temperature profiles for SES cells tested at 0˚C, 25 ˚C and 45 ˚C, grouped by C-rate. Tested at Exponent.

Appendix 2 – Eclipse Energy testing data

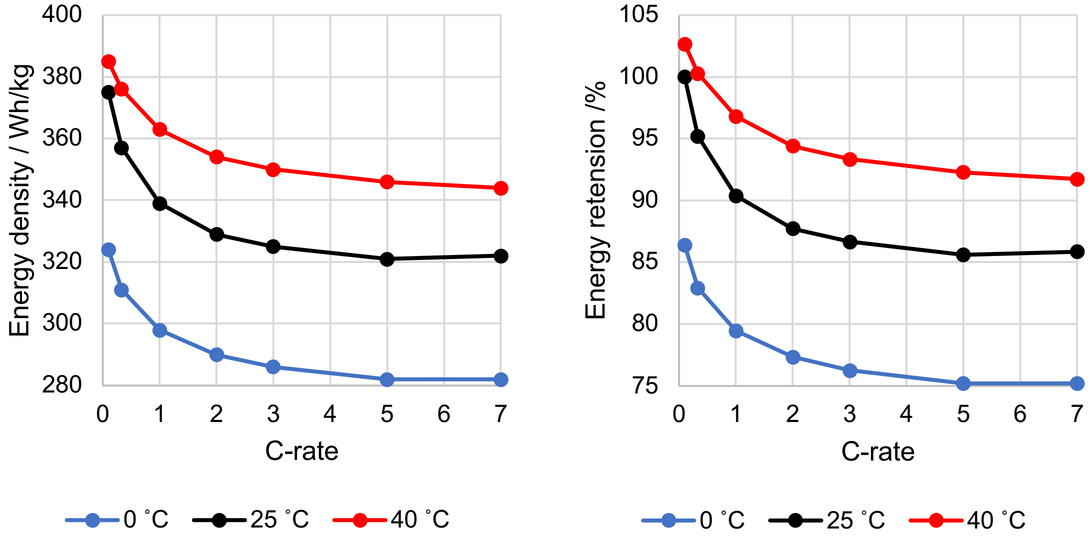

Figure 8: Energy density at different C-rates (left) and energy retention relative to 0.1 C energy at 25℃ from Eclipse Energy.

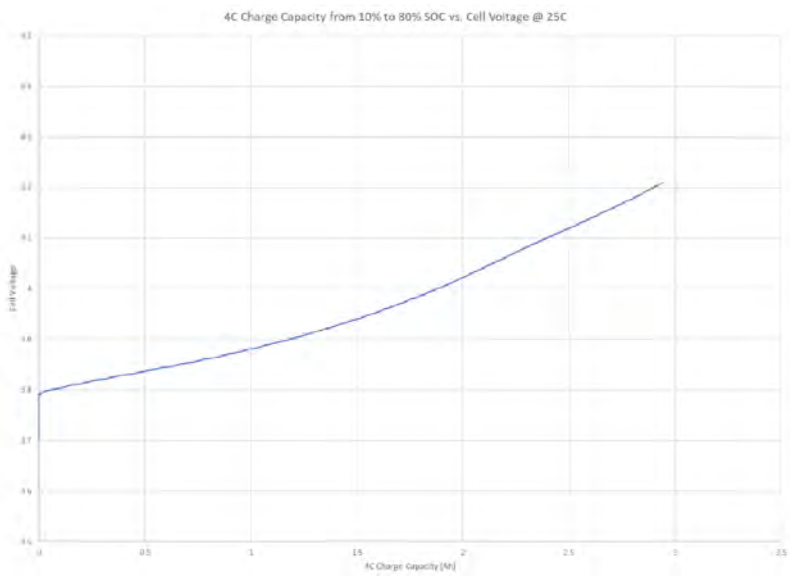

Figure 9: Fast charging data for the SES cells at 25℃ from 10%-80% state-of-charge at 4C taking 10.5 mins. Tested at Eclipse Energy.[5]

[5] Note that the fast charging at 4C (16.8 A) started at a state-of-charge of 10% (0.42 Ah) and continued to 80% (3.36 Ah) thus representing charge throughput of 2.94 Ah as shown in the data. Here, the cell voltage remained below the upper cell voltage limit of 4.3 V demonstrating a charge time from 10-80% state-of-charge of 10.5 minutes.

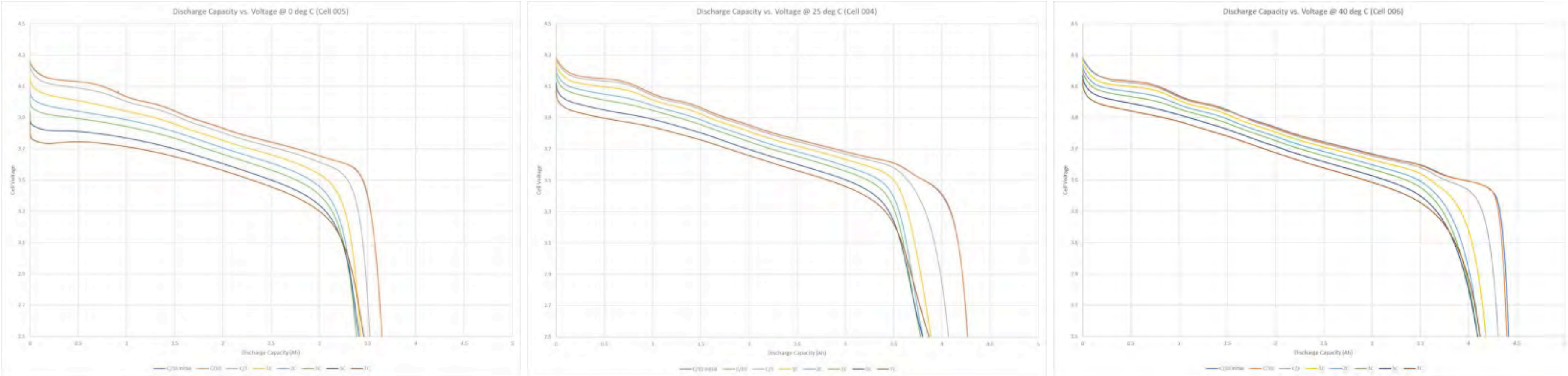

Figure 10: Voltage profiles for SES cells tested at 0˚C, 25 ˚C and 45 ˚C, grouped by temperature. Tested at Eclipse Energy.

Appendix 3 – Discharge testing procedure

- Capacity check
    - Rest for 2 hrs in each different temperature chamber (0°C, 25°C, or 40°C)
    - Constant current charge at 0.1C (0.42 A) until voltage = 4.3 V
    - Constant voltage hold at 4.3V until current <0.05C (0.21 A)
    - Rest for 20 minutes
    - Constant current discharge at 0.1C (0.42 A) until voltage = 2.5 V
    - Rest for 20 mins
- Rate capacity test (0.1C)
    - Constant current charge 0.33C (1.4 A) until voltage = 4.3 V
    - Constant voltage hold at 4.3 V until current < 0.05 C (0.21 A)
    - Rest for 10 mins
    - Constant current discharge at 0.1C (0.42A) until voltage = 2.5 V
    - Rest for 30 mins
- Rate capacity test (0.33C)
    - Constant current charge 0.33C (1.4 A) until voltage = 4.3 V
    - Constant voltage hold at 4.3 V until current < 0.05 C (0.21 A)
    - Rest for 10 mins
    - Constant current discharge at 0.33C (1.4 A) until voltage = 2.5 V
    - Rest for 30 mins
    - Constant current discharge at 0.1 C (0.42 A) until voltage = 2.5 V
    - Rest 10 mins
- Rate capacity test (1C)
    - Constant current charge 0.33C (1.4 A) until voltage = 4.3 V
    - Constant voltage hold at 4.3 V until current < 0.05 C (0.21 A)
    - Rest for 10 mins
    - Constant current discharge at 1C (4.2 A) until voltage = 2.5 V
    - Rest for 30 mins
    - Constant current discharge at 0.1 C (0.42 A) until voltage = 2.5 V
    - Rest 10 mins
- Rate capacity test (2C)
    - Constant current charge 0.33C (1.4 A) until voltage = 4.3 V
    - Constant voltage hold at 4.3 V until current < 0.05 C (0.21 A)
    - Rest for 10 mins
    - Constant current discharge at 2C (8.4 A) until voltage = 2.5 V
    - Rest for 30 mins
    - Constant current discharge at 0.1 C (0.42 A) until voltage = 2.5 V
    - Rest 10 mins
- Rate capacity test (3C)
    - Constant current charge 0.33C (1.4 A) until voltage = 4.3 V
    - Constant voltage hold at 4.3 V until current < 0.05 C (0.21 A)
    - Rest for 10 mins
    - Constant current discharge at 3C (12.6 A) until voltage = 2.5 V
    - Rest for 30 mins
    - Constant current discharge at 0.1 C (0.42 A) until voltage = 2.5 V
    - Rest 10 mins
- Rate capacity test (5C)
    - Constant current charge 0.33C (1.4 A) until voltage = 4.3 V
    - Constant voltage hold at 4.3 V until current < 0.05 C (0.21 A)

- Rest for 10 mins
    - Constant current discharge at 5C (21 A) until voltage = 2.5 V
    - Rest for 30 mins
    - Constant current discharge at 0.1 C (0.42 A) until voltage = 2.5 V
    - Rest 10 mins
- Rate capacity test (7C)
    - Constant current charge 0.33C (1.4 A) until voltage = 4.3 V
    - Constant voltage hold at 4.3 V until current < 0.05 C (0.21 A)
    - Rest for 10 mins
    - Constant current discharge at 7C (29.4 A) until voltage = 2.5 V
    - Rest for 30 mins
    - Constant current discharge at 0.1 C (0.42 A) until voltage = 2.5 V
    - Rest 10 mins

Appendix 4 – Fast charging protocol

- Initial discharge
    - Constant current discharge at 0.1C (0.42 A) until voltage = 2.5 V for conditioning
    - Rest for 10 mins
- Capacity check cycle
    - Constant current charge at 0.33C (1.4A0 until voltage = 4.3V
    - Constant voltage hold at 4.3V until current < 0.05C (0.21 A)
    - Rest for 10 mins
    - Constant current discharge at 0.33C (1.4 A) until voltage = 2.5 V
    - Rest for 30 mins
    - Constant current discharge at 0.1C (0.42 A) until voltage = 2.5V for conditioning
    - Rest for 10 mins
- 4C fast charge
    - Constant current charge at 0.33C (1.4 A) until charge capacity = 0.42 Ah (10% state-of-charge of 4.2 Ah)
    - Rest for 10 mins
    - Constant current charge at 4C (16.8 A) until either charge capacity = 3.36 Ah (SoC 80% of 4.2 Ah, total fast-rate charge capacity of 2.94) or Voltage = 4.3V
        - If voltage limit reached, constant voltage hold at 4.3 V until charge capacity = 3.36 Ah (SoC 80% of 4.2 Ah, total fast-rate charge capacity of 2.94)
    - Rest 10 mins
    - Constant current discharge at 0.33C (1.4 A) until voltage = 2.5 V
    - Rest for 10 mins

Appendix 5 – External short circuit testing set-up and data

Test conditions

- Circuit formed using 3/0- and 2/0-gauge cables and controlled with a 12VDC rlay
- Current sensing was performed using a 0.25 mΩ calibrated shunt resistor
- External resistance: ~4.8 mΩ
    - o 1 kHz AC impedance measured using a Hioki battery tester
- Sample rate: 10 Hz (100 ms/sample)
- Temperatures recorded: positive tab, negative tab, clamp centre, and ambient
- Circuit was opened for 10 minutes using digital timer
- Temperature and voltage was monitored for one hours after end of short-circuit

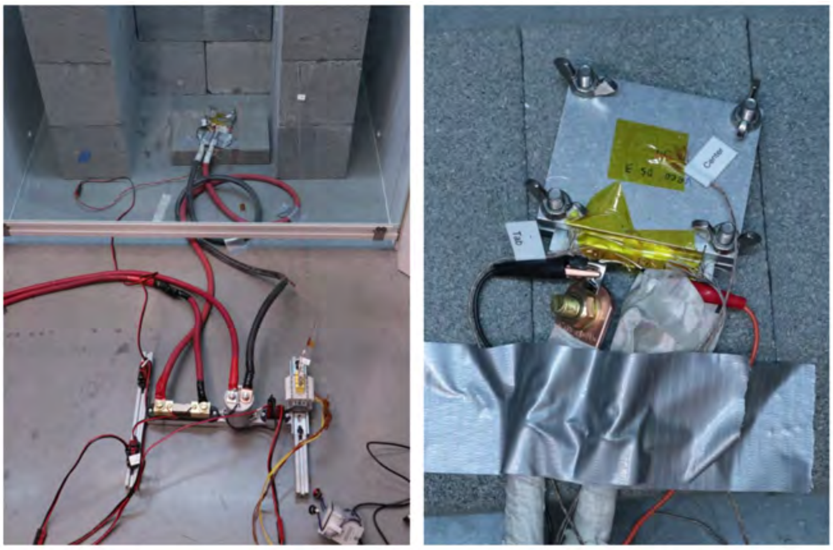

Figure 11: Short-circuiting test set-up conducted by Exponent.

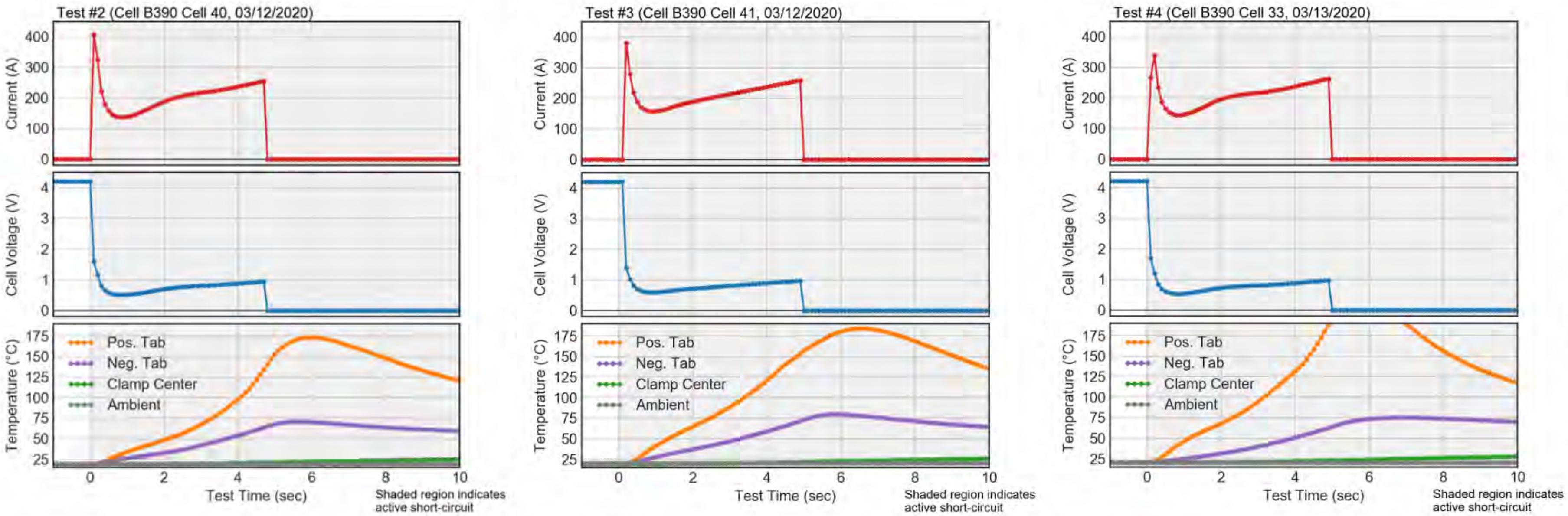

Figure 12: External short-circuit test data with 3 repeats performed at Exponent.[6]

[6] Note that an additional cell was tested and passed the external short-circuit test, however due to an error in the data logging this has not been shown for clarity of communication. The abrupt drop in short-circuit current and voltage drop to 0 V is due to the positive tab being fused open due to the localised heating.

Appendix 6 – Overcharge test set-up and results

Test conditions

- Charge at 1C (2.89 A) stopping at 8.5 V (2 x charge voltage) or after one hour (200% SOC)
- Sample rate: 1 Hz (1 second/sample)
- Temperature recorded: positive tab, negative tab, clamp centre, and ambient
- Temperature and voltage monitored for one hour after charge termination

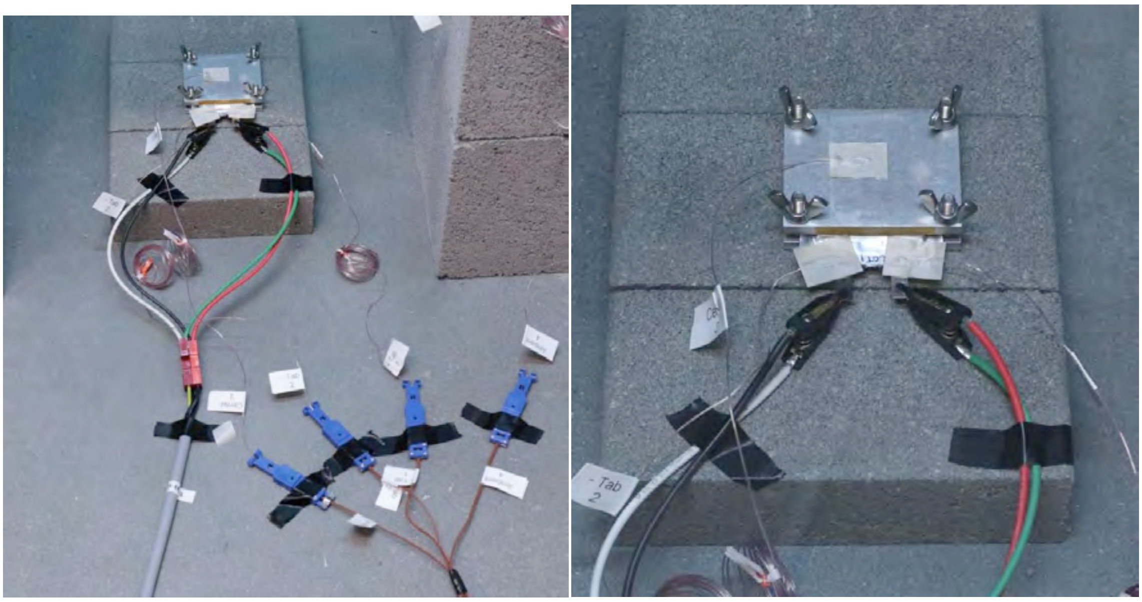

Figure 13: Overcharge cell test set-up performed at Exponent.

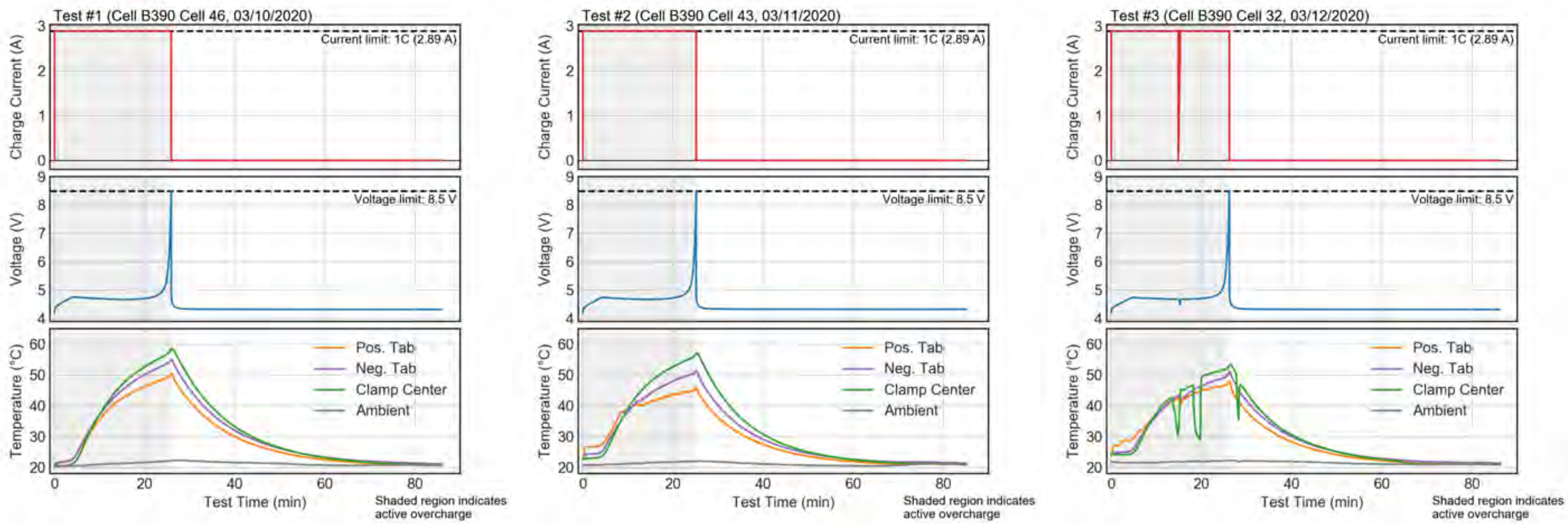

Figure 14: Overcharge tests with 3 repeats performed at Exponent.[7]

[7] Note that in test number 3, the centre thermocouple lifted off from the cell three times during the test and was manually placed back on. This did not interfere with the maximum temperature measured at the end of charge. The test was also paused for 28 seconds in response to the first thermocouple release. This time is included in the data for completeness.

Appendix 7 – Nail penetration test set-up and data

Test conditions

- Nail controlled by hydraulic cylinder with 75 mm stroke length
- Hight adjusted to penetrate cell by <5 mm
- Sample rate: 10 Hz (100 ms/sample)
- Temperatures recorded positive tab, negative tab, clamp center and ambient
- The nail was left inserted into the cell for at least 30 minutes or until cell rupture occurred
- All three (3) tests were performance using the “Slow” nail speed (≤5 mm/s) at ambient temperature

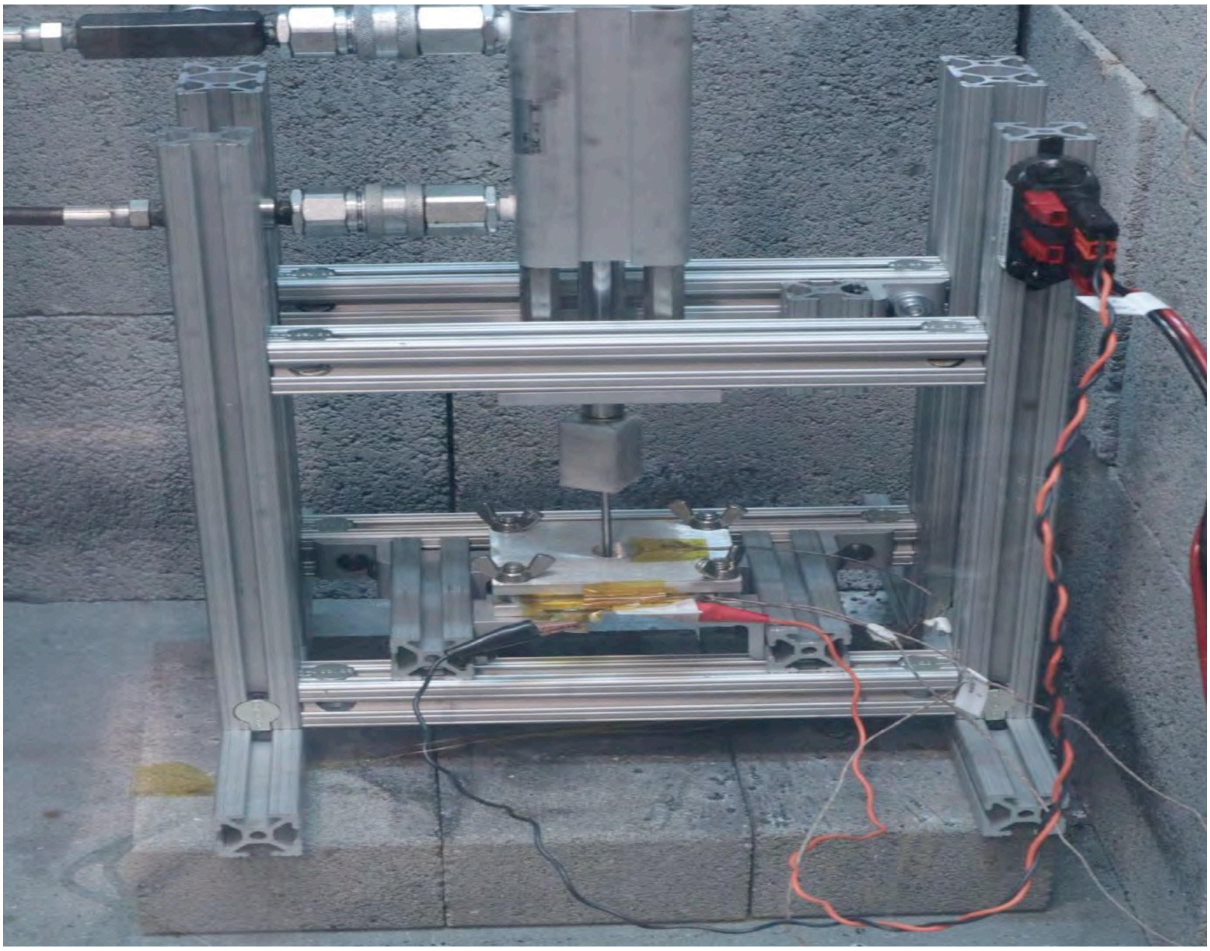

Figure 15: Nail penetration test set-up performed at Exponent.

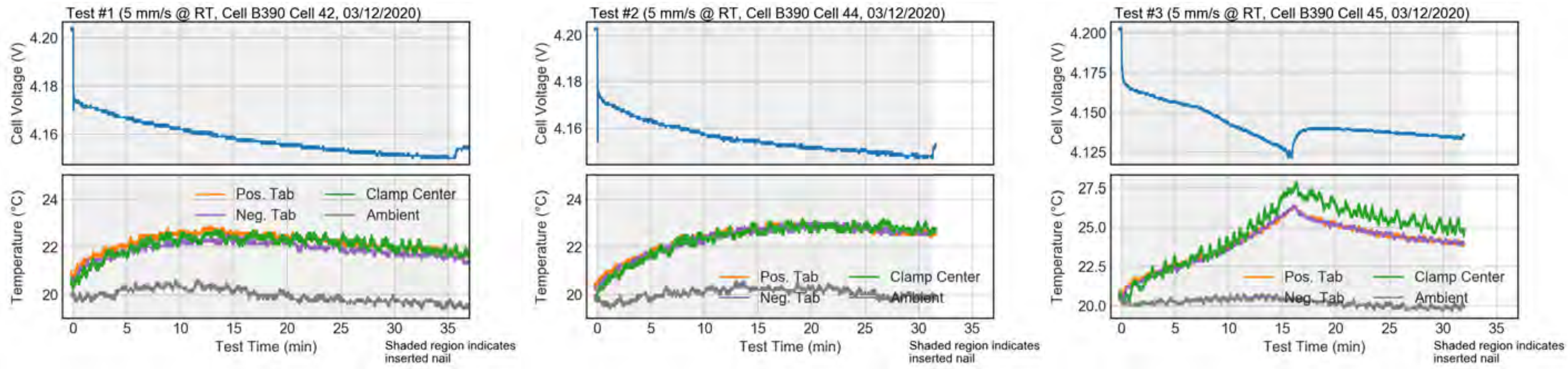

Figure 16: Nail penetration testing results with 3 repeats performed at Exponent.

Appendix 8 – ARC test set-up and data

- ARC testing was performed on 2 SES lithium-metal cells
- Prior to ARC testing, each cell was charged with a constant current of 0.64 A to 4.25 V with a constant voltage hold to a 0.16 AA cut-off
- The cell was clamped between two metal plates (Figure 17) with 4 lbf.in of torque used to tighten each nut of the compression rig tie rods
- The cell with clamp was suspended in the ARC chamber without being in contact with the chamber wall
- Voltage leads (yellow arrows in Figure 18) were connected to the cll, and an xternal data-logger
- The ARC control thermocouple (red arrow in Figure 18) was affixed to one side of the cell with high-temperature adhesive tape and two auxiliary thermocouples were affixed to both sides of the cell (white allows in Figure 18)
- The cells were tested with the following ARC settings:
    - o Temperature range: 50 °C to 400 °C
    - o Heat step size: 5 °C
    - o Slope sensitivity: 0.02 °C/min
    - o Wait/search time: 25 min/10 min (35 min total)

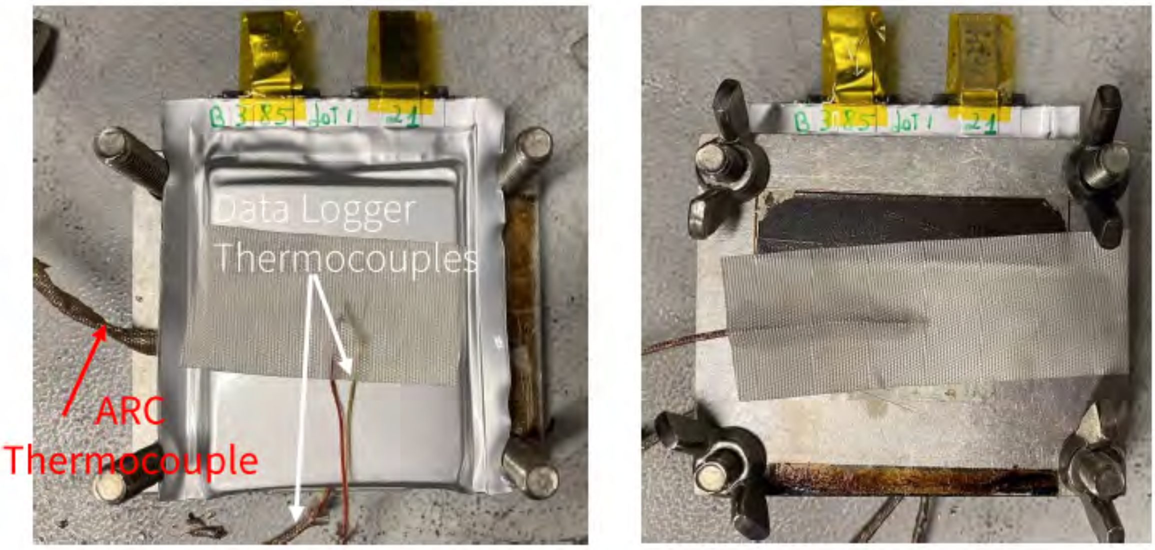

Figure 17: Images of cell compression jig and location of thermocouples for ARC testing.

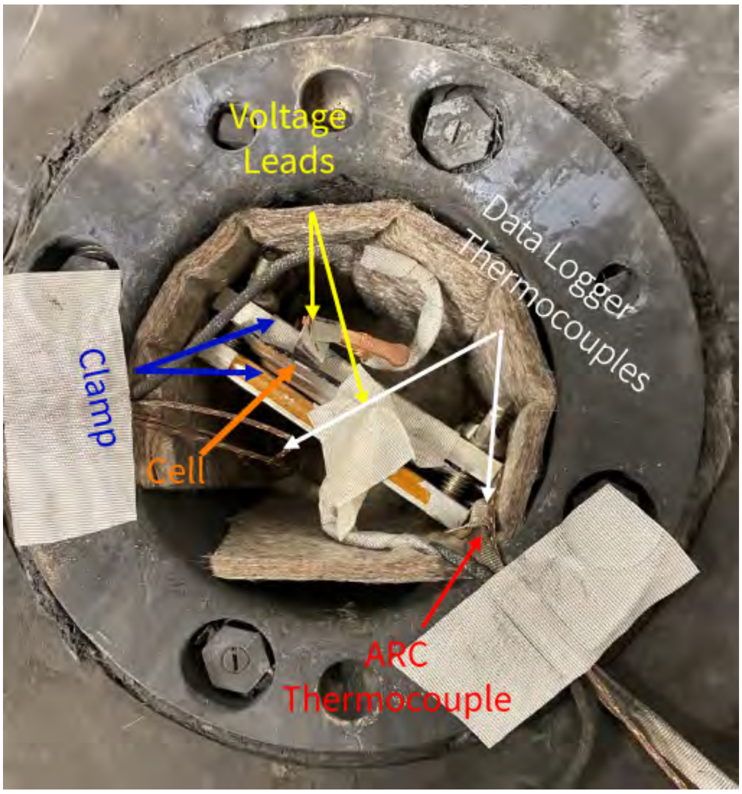

Figure 18: Cell with clamp installed in ARC chamber.

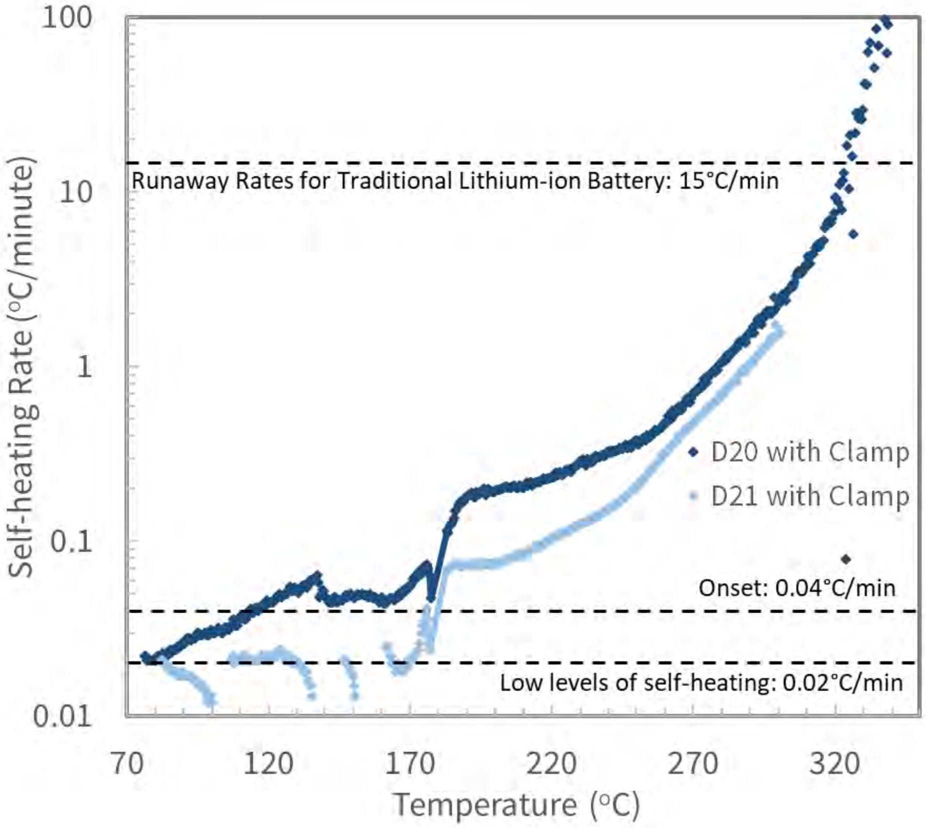

Figure 19: ARC testing results performed at Exponent.[8]

- The onset temperature where self-heating rates exceed 0.04 °C/min occurred between 115-176 °C
- Cell D20 exhibited a thermal runaway temperature of 324°C where thermal runaway is defined as a self-heating rate in excess of 15°C/min
    - o This is attributed to the thermal stability of the high nickel cathode which is the same for other batteries using a high-nickel cathode
- No sudden self-heating was observed at the lithium melting temperature of ~180°C indicating good thermal stability between molten lithium and the electrolyte

[8] Due to a testing protocol error (cooling kicked on at 300°C), D21 did not experience thermal runaway

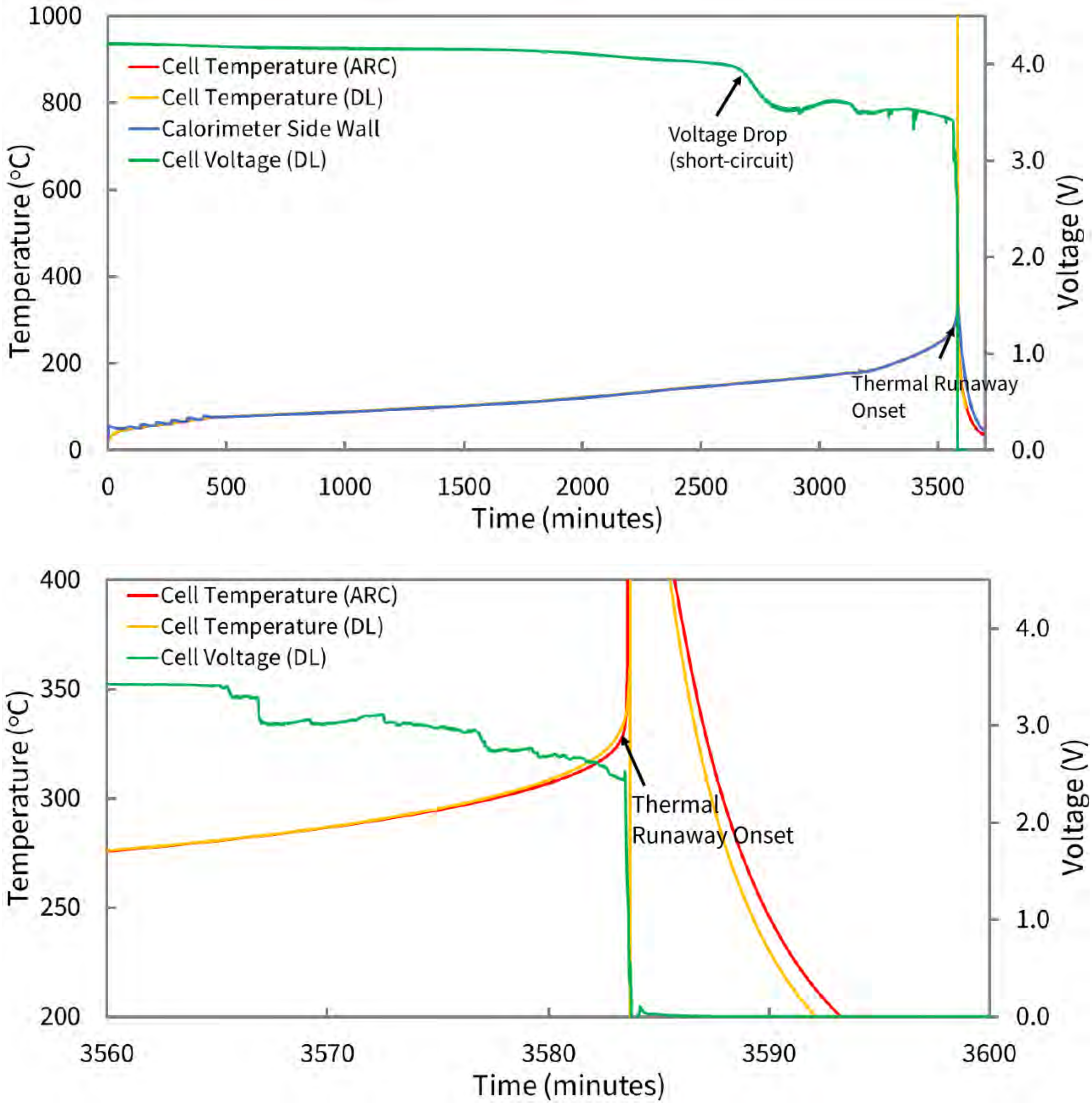

Figure 20: ARC test results for cell D20 with full test data (top) and zoom in of the data (bottom) performed at Exponent.

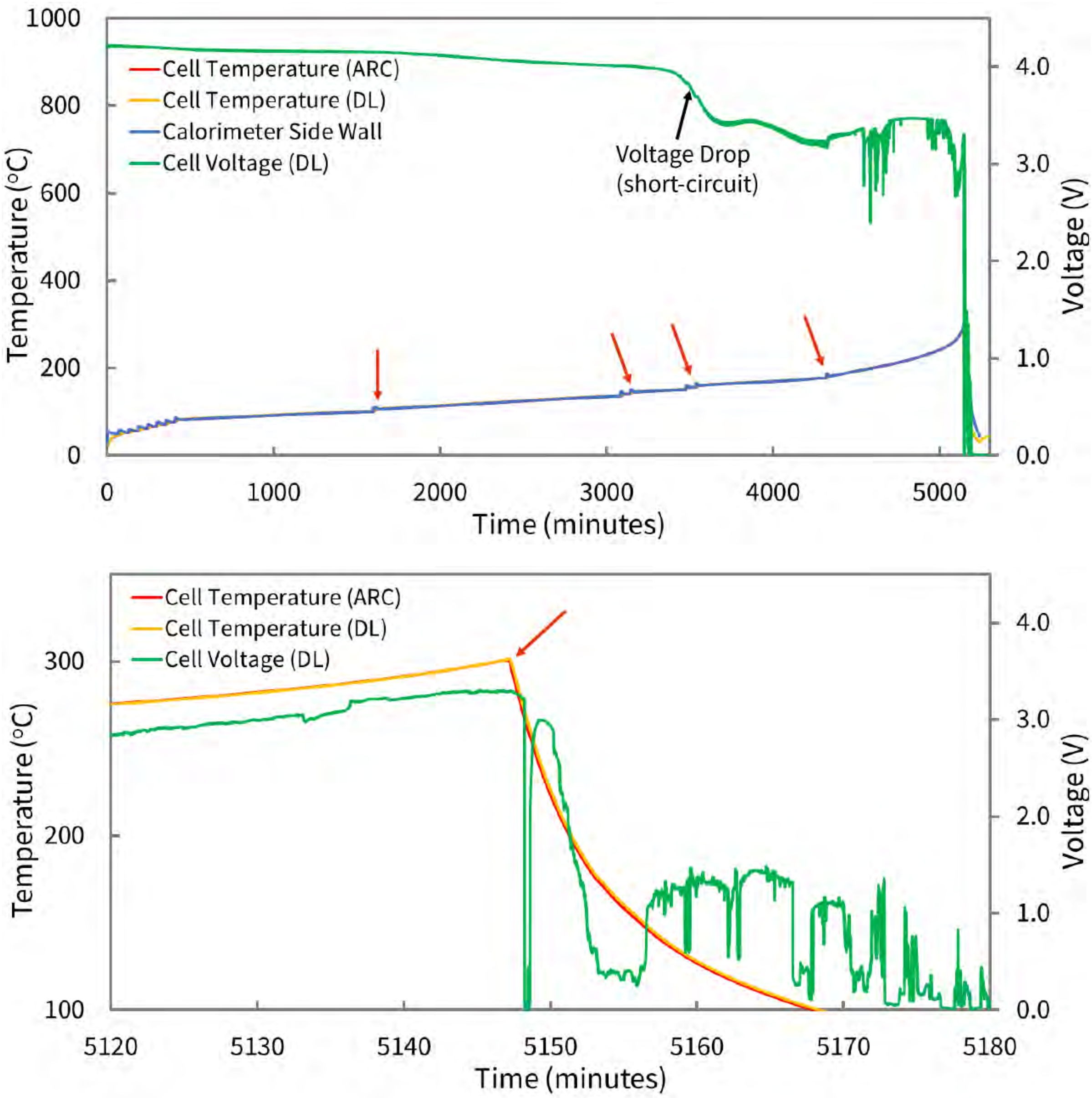

Figure 21: ARC test results for cell D21 with full test data (top) and zoom in of the data (bottom) performed at Exponent.[9]

[9] Cell D21 did not experience thermal runaway due to testing protocol error, activating the cooling air at ~300 °C early (red arrow of bottom plot). Low inconsistent levels of self-heating were observed from ~82°C-84°C. The low levels of self-heating stopped and resumed multiple times between 84°C-169°C (red arrows of top plot)

References

[1] Exponent, SES cell electrical tests, 2021.

[2] Eclipse Energy, Test Report: RPT-21-635_Ivanhoe_Cell Characterization_Rev.1, 2021.