United States
Consumer Product Safety Commission

August 2024

CPSC Staff Statement[1] on Contractor eBike Battery Test Report

The attached redacted June 2024 report presents the findings of Exponent, Inc. from their research study on electric bicycle (eBike) battery packs. Under Order No. 61320623P0045, CPSC sponsored this exploratory study of e-bike battery pack charging under abnormal environmental and charger conditions. Exponent selected five battery packs for the evaluations. Two packs were from commercially available eBikes (original equipment manufacturer, or OEM), two were considered third-party replacement packs for the same eBikes (aftermarket for specified model eBike), and one pack was selected as a typical economical option unassociated with a particular eBike (generic aftermarket). The report shorthand refers to these batteries as Pair 1 OEM - Pack, Pair 2 OEM – Pack, Pair 1 Rep – Pack, Pair 2 Rep – Pack and Solo, respectively. The two commercially available eBikes were third-party certified to the consensus voluntary standard, ANSI/CAN/UL 2849 - *Standard for Safety for Electrical Systems for eBikes*, which considers the safety of the whole e-bike electrical system (battery pack, charger, bike). Pair 2 OEM – Pack was certified to ANSI/CAN/UL 2271 – *Standard for Safety for Batteries for Use in Light Electric Vehicle (LEV) Applications*, one of the battery standards permitted by UL 2849. None of the replacement battery packs were third-party certified to the consensus battery standards for e-bikes.

The testing included four main conditions: ambient temperature increasing during charging; ambient temperature decreasing during charging; out-of-specification charger current test; and out-of-specification charger voltage test. These tests were intended to provide insight into differences in the levels of protection that OEM versus aftermarket batteries and chargers provide and potential effects that out-of-specification operation may have on the safety of the lithium-ion cells in the battery pack. Despite the limited sample set, the testing revealed several instances where the battery pack battery management systems (BMS) allowed deviations in temperatures beyond the cell specification limits and accepted charge voltages in excess of the specified charger. One of the batteries failed to terminate charging after reaching the minimum charging current cut-off, possibly allowing overcharging. In most of the cases of deviations from the specifications, no cell damage was detected. However, destructive analysis of the cells in the Solo pack showed early signs of internal degradation (lithium plating) that could eventually lead to problems ranging from early performance drop to internal shorting up to thermal runaway in its most extreme. Overall, even with this limited sample set, the assessment highlights the importance of a robust BMS design, aligned closely with the cell specifications and high-quality cells certified to an applicable standard, ANSI/UL 1642 - *Lithium Batteries*, for example.

CPSC staff will use the results of this testing to support standards improvement efforts.

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[1] This statement was prepared by the CPSC staff, and the attached report was prepared by Exponent, Inc. for CPSC staff. The statement and report have not been reviewed or approved by, and may not represent the views of, the Commission.

Consumer Product Safety Commission Lithium-ion Safety Performance

Consumer Product Safety Commission
Lithium-ion Safety Performance

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Acronyms and Abbreviations

A	amp
Ah	amp-hour
BMS	battery management system
BMU	battery management unit
BOM	bill of material
CC	constant current
CC-CV	constant current-constant voltage
CID	current interruption device
C-rate	capacity rate (rate to discharge cell in 1 hour)
CT	computed tomography
CV	constant voltage
DC	direct current
DPA	destructive physical analysis
E-bike	electrical bicycle
EDS	energy dispersive spectroscopy
FET	field effect transistor
GB	National Standards of the People's Republic of China
Hz	hertz
IEEE	Institute of Electrical and Electronics Engineers
Li-ion	lithium-ion
MOSFET	metal oxide semiconductor field effect transistor
mA	milliampere
Mfr.	manufacturer
mm	millimeter
mV	millivolt
NCA	nickel-cobalt-aluminum
NMC	nickel-manganese-cobalt
OEM	original equipment manufacturer
PCB	printed circuit board
Rep	Replacement
SEI	solid electrolyte interphase
SEM	scanning electron microscopy
SOC	state of charge
TOCC	top-off charge criterion
TOCV	top-off charge voltage
UL	Underwriters Laboratory
V	volt
PFS	positive-facing separator
NFS	negative-facing separator
µm	micrometer

Executive Summary

The testing and analysis detailed in this report provides a limited snapshot into the current state of the e-bike industry with regards to the functionality and safety of e-bike battery packs. The results were evaluated against the specific testing protocols, industry best practices, and Exponent, Inc.'s (Exponent) experience.

Five types of battery packs were selected for evaluation (Section A). Two packs are from commercially available e-bikes, two are considered third party replacement packs for the same e-bikes, and one pack was selected as a typical economical option unassociated with any particular e-bike. The two commercially available e-bikes and their battery packs are certified to industry standard UL 2849, which considers the electronic safety of the whole e-bike system (pack, charger, bike).

The core of this project involved evaluating the performance of the packs against four testing protocols (Sections C through F). The protocols generally probe the ability of the packs to accept charge under abnormal or unintended temperature, voltage, and current conditions.

Sections C and D evaluate the charging behavior of packs that begin their charge at an ambient temperature (23 °C) and either increase or decrease to temperatures beyond the limits defined in the cell specifications. Only one of the five packs limited the charging once it reached a specific elevated temperature, notably at a temperature consistent with the cell specifications. None of the packs limited charging at low temperatures. In all but one case, the cells in the packs appeared to have experienced temperatures during charging beyond the cell specification allowable range.

From testing detailed in Section B.3, three of five packs were found to include functionality to limit charging to a particular temperature range, one pack was only observed to have a limit at an elevated temperature, and one did not prevent charging within any of the tested temperatures. At a minimum, the five packs appear to be set with at least one of the two temperature range limits out of agreement with the cell specification.

Sections E and F evaluate the ability of the packs to handle charging with an unintended charger that provides a higher than intended output voltage or output current. In the case of the higher than intended current (Section E), all five packs were able to complete their charging protocol. In fact, due to the testing setup, where the packs were also allowed to charge past the intended upper voltage, the packs were found to be able to charge both faster and at a higher rate than what the intended charger provides as an output. It is important to note that a pack may be able to accept a charge rate higher than the intended charger, per the specifications, and each instance would need to be assessed for signs of damage.

In the case of testing with a higher than intended output voltage from the charger (Section F), all five packs were able to complete their charging protocol. Charging was terminated with the pack's overvoltage protection, indicating that the pack BMS does not modulate the input voltage, but rather accepts the voltage and monitors the cells/pack voltage to limit the charge. Since the packs terminated charge at the overvoltage protection limit in a constant current mode, and because the setpoint of the overvoltage protection limit was close to the intended upper voltage and sometimes still within the cell specification, the cells appear unlikely to be significantly damaged within a limited range of charge cycles (30). This was supported by teardown analysis of cells that were cycled to simulate the observations of Section F pack testing.

Exponent performed a limited pack construction quality assessment of the five pack types, focusing on aspects of construction quality, circuit board cleanliness, and overall design (see Section B.2). Some common positive design aspects and common weaknesses were observed across the packs. For example, they all lack adequate sealing along the enclosures and charge/discharge ports making them prone to moisture and dust ingress. Numerous other observations of design choices and weaknesses specific to each pack type were also documented.

Exponent also performed a limited set of electrical tests on the packs outside of the core testing protocols (Sections C through F). This information, detailed in Section B.3, provided both an insight into how these products compare with state-of-the-art battery packs and helped interpret and contextualize the findings in Sections C through F. Two sets of observations were made that are against industry best practices. First, it was found that the Pair 2 Rep – Pack and Charger combo results in the pack being float charged,[1] which is likely to cause the cells to be overcharged with extended time on charge. Second, the packs exhibited varying degrees of ability to limit the charge to a particular temperature range that is in line with the cell specifications, including one pack that did not exhibit any limits.

Exponent evaluated the construction quality of the cells in the packs through use of computed tomography (CT) scanning, physical teardowns, and limited charge-discharge cycling. The cells sourced in the packs are generally constructed according to industry best practices. One cell type exhibited signs of lithium plating after limited cycling, but the safety risk posed by the presence of plated lithium requires further analysis.

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1 Float charging is defined as the application of low levels of charging current for long periods of time, often with no limit on the length of time.

Introduction

This report details findings by Exponent on e-bike battery packs intended to further the Consumer Product Safety Commission's (CPSC) understanding of the state of the e-mobility industry as it relates to the safety of lithium-ion (Li-ion) battery packs.

The scope of this project was generated in response to the Performance Work Statement (PWS) included in Solicitation Notice ID CPS-2114-23-0019 – "Developing and Executing a Research Contract to Assess the Impact of E-bike and E- Mobility Device Charging Under Dynamic Temperature Conditions including Charging and Discharging at Ambient Temperature Extremes."

Project Background and Motivation

Safe use of lithium-ion batteries is dependent on the ability of the product to function within the intended operation conditions regardless of the external environmental or electrical conditions. Any use of lithium-ion batteries outside of these conditions can cause damage and potentially lead to their failure. Because of the nature of lithium-ion batteries (i.e., stored energy combined with flammable and combustible materials), failures can lead to hazardous situations for the user. Worst-case failure scenarios can result in thermal runaway of the battery, a condition leading to the production of fire, hot gas, and ejecta.[2]

In electric micro-mobility products such as e-bikes, the extent of damage and hazard has been, regrettably, demonstrated through high-profile incidents.[3,4] Due to the large size of the battery

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2 Faenza, N., Spray, R., and Kuykendal, M., "Understanding the Fundamental Mechanisms of Battery Thermal Runaway Propagation and Mitigation," SAE Technical Paper 2023-01-1515, 2023, https://doi.org/10.4271/2023-01-1515, https://doi.org/10.4271/2023-01-1515.

3 T. f. TFL Announces Safety Ban of E-Scooters on Transport Network (2021), https://tfl.gov.uk/info-for/media/press-releases/2021/december/tfl-announces-safety-banof-e-scooters-on-transport-network. T. f. TFL Announces Safety Ban of E-Scooters on Transport Network (2021), https://tfl.gov.uk/info-for/media/press-releases/2021/december/tfl-announces-safety-banof-e-scooters-on-transport-network.

4 R. S. Charge Safe, NYC's Electric Micromobility Action Plan (2023), https://nyc.gov/assets/home/downloads/pdf/office-of-the-mayor/2023/micromobility-action-plan.pdf. R. S. Charge Safe, NYC's Electric Micromobility Action Plan (2023), https://nyc.gov/assets/home/downloads/pdf/office-of-the-mayor/2023/micromobility-action-plan.pdf.

packs in e-bikes compared with other consumer electronic devices, a thermal failure can result in a substantial safety hazard that is difficult to contain.[5]

The safe use of an e-bike battery pack depends on a number of factors, including:

1. The quality of the lithium-ion cells in the pack
2. The design and construction quality of the pack
3. The functionality of the battery management system (BMS) to limit the use of the pack to predefined conditions
4. The performance of the charger
5. The maintenance and care of the pack by the user as defined in the product instruction manual

In Section B of this report, the battery packs selected for this study are evaluated against industry best practices with regards to the design and construction quality of the pack, the functionality and safety components of the pack, and the construction quality of the cells. This information provides a limited snapshot into the state of the e-mobility industry.

The BMS has two primary functions in an e-bike battery pack. The first function is to keep the cells within their intended operating parameter ranges during normal operation of the e-bike. At a minimum, the BMS typically monitors values of temperature, voltage, and current and prevents the cells from experiencing conditions outside of their specifications. The second function is to perform actions that limit damage in the event of an unintended scenario or failure (i.e., safety protections).

Sections C and D detail the results of specific tests performed on packs intended to characterize their ability to respond to variable temperature conditions during charging and keep the cells within their intended normal parameter ranges. These test protocols provide insight into the functionality of each pack's BMS.

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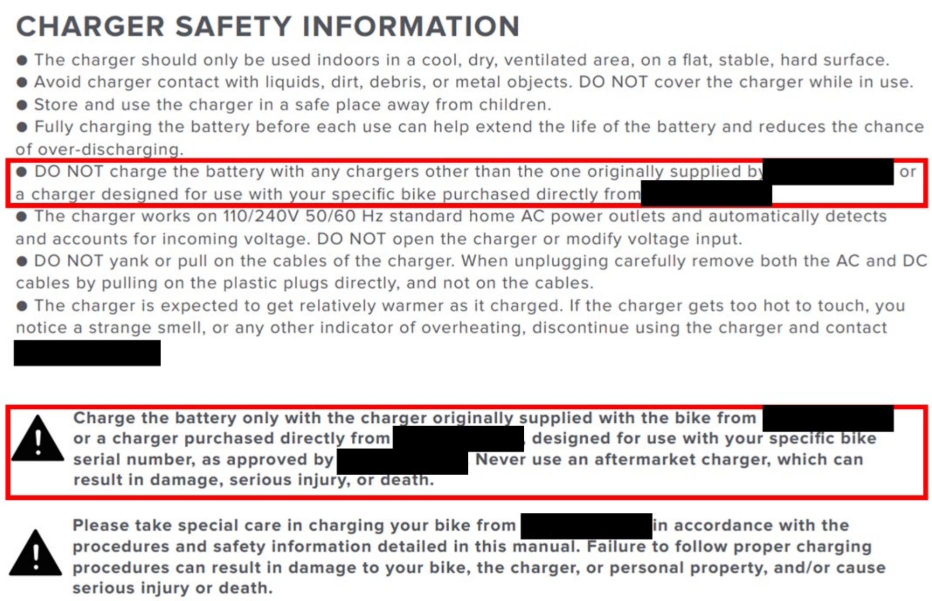
[5] Daniel A. Torelli *et al* 2024 *ECS Adv.* **3** 010501.

One scenario that relies on the ability of the BMS is when an unintended charger is used to charge a battery pack. E-bikes and e-bike battery packs are often supplied with a charger. The provided original equipment manufacturer (OEM) charger is presumably designed with specific metrics that are compatible with the corresponding battery pack charging protocol. E-bike manufacturers are generally aware of the need to use the correct charger, and sometimes put warnings to this effect in the instruction manuals (Figure 1) or directly on the product.



CHARGER SAFETY INFORMATION

- The charger should only be used indoors in a cool, dry, ventilated area, on a flat, stable, hard surface.
- Avoid charger contact with liquids, dirt, debris, or metal objects. DO NOT cover the charger while in use.
- Store and use the charger in a safe place away from children.
- Fully charging the battery before each use can help extend the life of the battery and reduces the chance of over-discharging.
- DO NOT charge the battery with any chargers other than the one originally supplied by [redacted] or a charger designed for use with your specific bike purchased directly from [redacted]
- The charger works on 110/240V 50/60 Hz standard home AC power outlets and automatically detects and accounts for incoming voltage. DO NOT open the charger or modify voltage input.
- DO NOT yank or pull on the cables of the charger. When unplugging carefully remove both the AC and DC cables by pulling on the plastic plugs directly, and not on the cables.
- The charger is expected to get relatively warmer as it charged. If the charger gets too hot to touch, you notice a strange smell, or any other indicator of overheating, discontinue using the charger and contact [redacted]

Charge the battery only with the charger originally supplied with the bike from [redacted] or a charger purchased directly from [redacted] designed for use with your specific bike serial number, as approved by [redacted] Never use an aftermarket charger, which can result in damage, serious injury, or death.

Please take special care in charging your bike from [redacted] in accordance with the procedures and safety information detailed in this manual. Failure to follow proper charging procedures can result in damage to your bike, the charger, or personal property, and/or cause serious injury or death.

Figure 1. Annotated image of warnings in a product manual regarding the use of charger that was not supplied with the battery pack.

The e-bike industry has recognized this as a key requirement for safety. Evaluation of "dedicated chargers for charging batteries" are within scope of industry standard ANSI/CAN/UL 2849:2022A – Standard for Safety: Electrical Systems for eBikes (referred to throughout this report as "UL 2849").

The motivations for the industry standard and manufacturer warnings stem from concerns that the use of an unintended charger can damage the battery pack. The battery pack BMS should have the ability to perform actions that protect the battery from damage that may be caused from the use of an unintended charger. The specific implementation of the actions can vary but should have the same result. Sections E and F evaluate scenarios where an unintended charger is used on an e-bike pack.

E-bike Charging Overview

The speed and extent to which a battery pack can be charged are primarily limited by the maximum allowable charge current, the upper voltage limit and the allowable temperature range. The exact values of these parameters are specific to each battery pack and are largely dictated by the limitations of the cells used to construct the pack; the values are traditionally determined through a combination of testing and reliance on the components' specifications (e.g., cell specifications, charge FET ratings, etc.). Generally, charging cells outside of the specified values can damage the cells. The specific damage to the battery depends on which parameter was exceeded and to what extent.

A full charge protocol of a lithium-ion battery typically involves two stages:

Stage 1 – A constant current is applied until the battery reaches the "Upper Voltage Limit." This stage is commonly referred to as a "Constant Current" or "CC" step.

Stage 2 – The battery is held at the voltage of the "Upper Voltage Limit" and the current is allowed to decrease as a function of demand from the battery pack until the current reaches the "Minimum Charging Current Cut-off" or a specified amount of time. This stage is commonly referred to as a "Constant Voltage" or "CV" step. Inclusion of both these charging stages (referred to as "CC-CV charging") is common practice for commercially available lithium-ion batteries.

The following text details four different charging scenarios to illustrate the impact on the parts of a typical lithium-ion battery charge protocol.

Scenario 1 (Figure 2) depicts a constant current charging implementation with no Upper Voltage Limit. Utilizing a charge protocol such as this will result in the lithium-ion battery being overcharged.

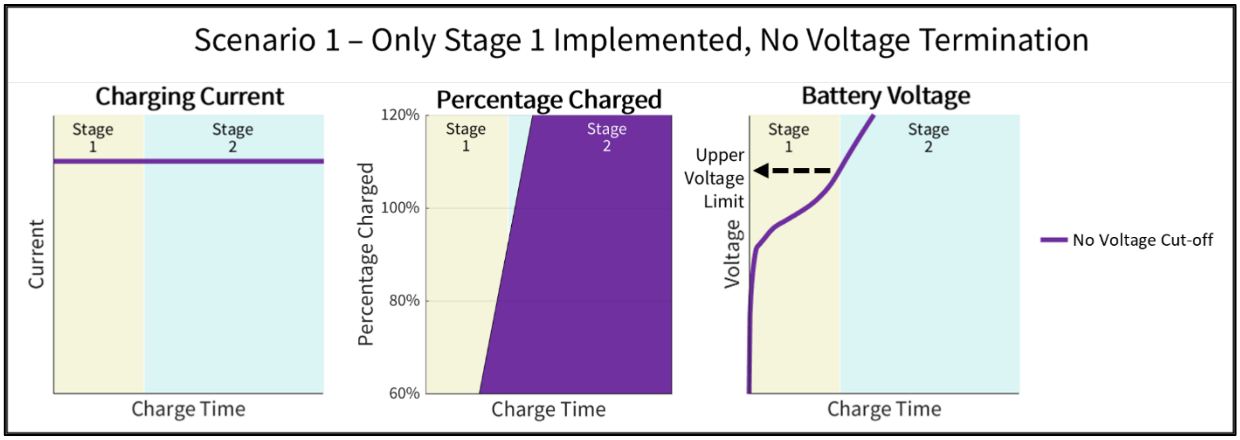


Figure 2. Schematic of a CC charging profile with no Upper Voltage Limit.

Scenario 2 (Figure 3) depicts the simplest charging protocol, where the battery is only charged using a constant current until it reaches the Upper Voltage Limit. A battery charged under this scenario will result in an incomplete charge.

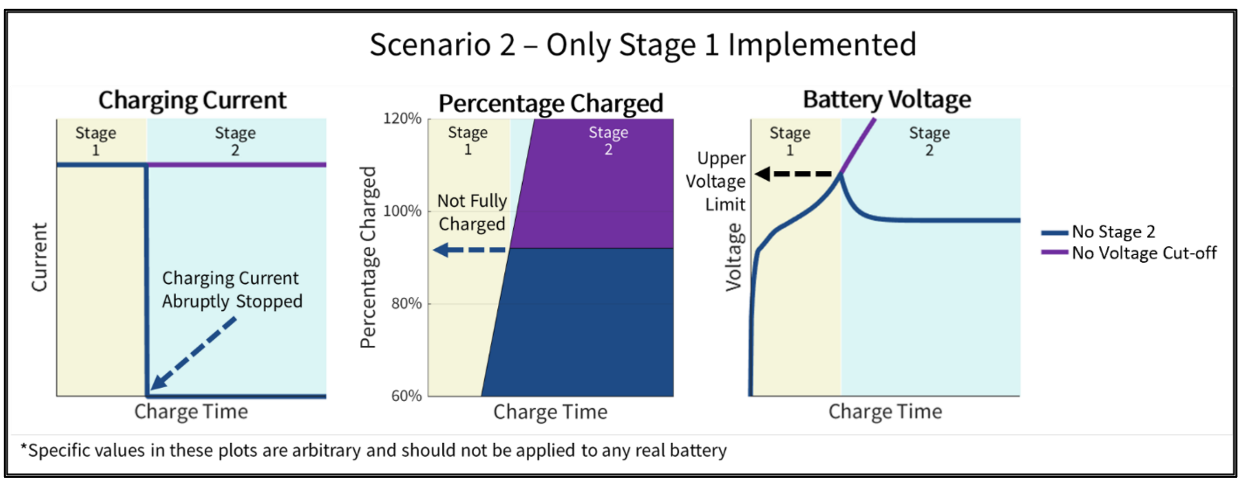


Figure 3. Schematic of a CC charging profile with an Upper Voltage Limit.

Scenario 3 (Figure 4) depicts a typical CC-CV charge protocol that results in a fully charged battery. Once current is removed (i.e., after the Minimum Charging Current Cut-off is reached), the battery open-circuit voltage will decrease by a small amount, commonly referred to as "voltage relaxation."

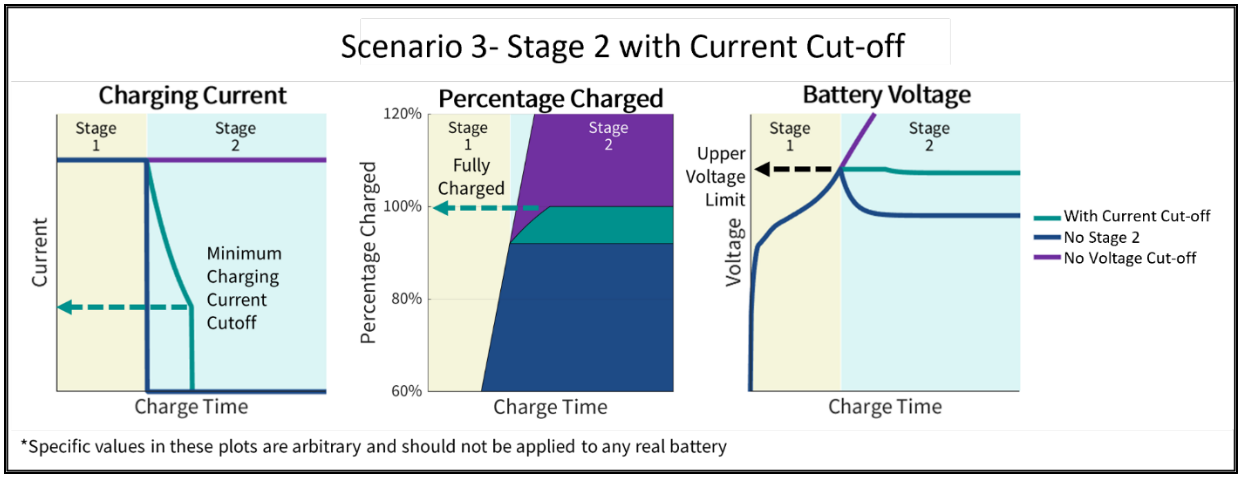


Figure 4. Schematic of a typical CC-CV charging profile.

Scenario 4 (Figure 5) depicts when the CV step is not terminated. This charge protocol will result in an overcharged battery. This is sometimes referred to as "float charging." Generally, lithium-ion batteries are not suitable for constant charging for infinite periods of time.

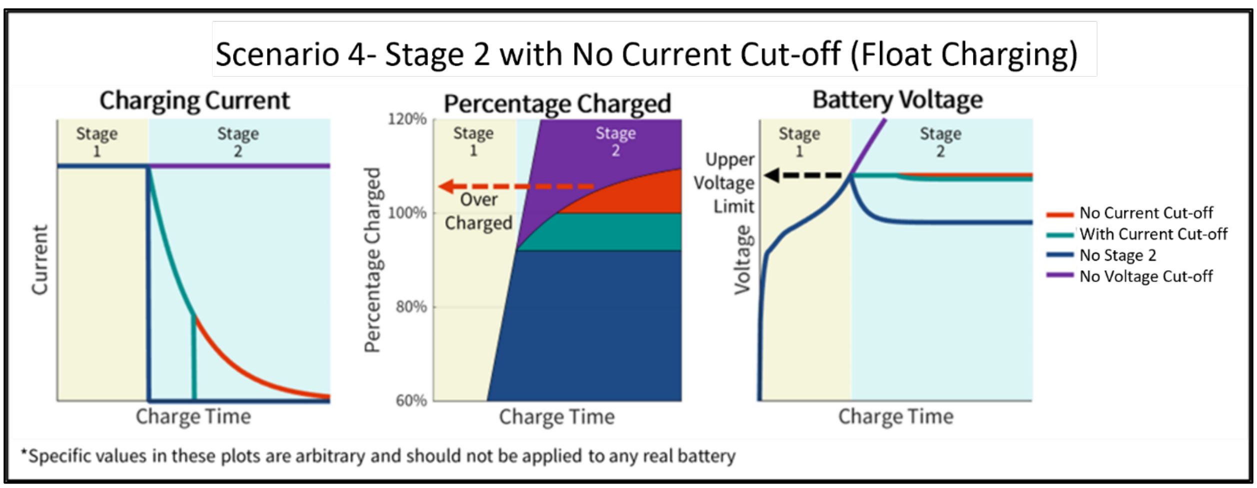


Figure 5. Schematic of a CC-CV charging profile with no Current Cut-off.

An e-bike battery system (i.e., battery pack and intended charger) will have a defined charging protocol that is controlled by the BMS and the charger. An unintended charger may provide a different output voltage and current and force the battery pack to restrict charging of the cells either by (1) completely preventing any charge current or (2) modulating the input voltage and current to the battery pack through components in the BMS circuit board such that the cells only experience voltages and currents within the allowable ranges.

The charger that is supplied with the e-bike is often rated for an output current below the maximum allowable current as defined in the cell specifications. Reasons for this difference can be technical, logistical, or financial. Charging faster than the rating of the intended charger does not necessarily mean that the pack is being abused.

Report Structure

This report details Exponent's findings from five testing protocols on five different e-bike battery packs. The first section (Section A – Sample Overview) provides an overview of the samples tested and the motivations for choosing them for this project. The next five sections summarize the results and findings of each of the testing protocols.

- Section B – Pack Construction and Safety Evaluation
- Section C – Ambient Temperature Increasing During Charging
- Section D – Ambient Temperature Decreasing During Charging
- Section E – Out-of-Specification Charger Current Test
- Section F – Out-of-Specification Charger Voltage Test

The overall findings and key takeaways from this project are above in the Executive Summary. Following the report, there are separate appendices for each of the Sections A – F that include supporting information and figures.

A. Sample Overview

Five battery pack models intended for use in an e-bike were evaluated in this project. The battery packs were selected using the following criteria:

- Two (2) pairs of battery packs (four packs total), with the packs within a given pair compatible with the same e-bike. Each pair consisted of:
  - One (1) original equipment manufacturer (OEM)[6] replacement battery for an e-bike that was certified to UL 2849.
  - One (1) aftermarket/third-party battery replacement (Rep) option with no UL certification.

- One (1) additional non-UL certified battery pack generically intended for use with an e-bike.

- Battery packs that did not present a conflict-of-interest for Exponent based on current and prior engagements with other clients.

Details of the components tested in this report are described in the following tables. There is a "Pack" and "Charger" for each supplier of a battery pack. The chargers were provided with the battery pack or purchased as the recommended product by the online marketplace that sold the battery packs. Throughout this report, the components will be referred to by the naming convention listed in Table 1.

Table 1. Report sample naming convention

Component	Group	OEM or Replacement
Pair 1 OEM – Pack	Pair 1	OEM
Pair 1 OEM – Charger	Pair 1	OEM
Pair 1 Rep – Pack	Pair 1	Replacement

[6] In this case, OEM refers to the company that manufacturers the full e-bike product, rather than the battery pack manufacturer that provides the packs as their identity is often unknown.

Component	Group	OEM or Replacement
Pair 1 Rep – Charger	Pair 1	Replacement
Pair 2 OEM – Pack	Pair 2	OEM
Pair 2 OEM – Charger	Pair 2	OEM
Pair 2 Rep – Pack	Pair 2	Replacement
Pair 2 Rep – Charger	Pair 2	Replacement
Solo – Pack	Solo	-
Solo – Charger	Solo	-

All five battery packs as outlined in Table 2 have a nominal voltage rating of 48 V and are composed of 18650 format lithium-ion cylindrical cells. Details for the compatibility of the two replacement battery packs with the OEM e-bike can be found in A.1 and A.2. Exponent did not verify through testing if the replacement battery packs were functional on the OEM e-bike, but instead relied upon online information.

Table 2. Battery packs tested

Pack	Production Date	Specifications
Pair 1 OEM	202303	48 V; 12.8 Ah
Pair 1 Rep	Not listed	48 V; 14 Ah
Pair 2 OEM	Not listed	48 V; 14 Ah
Pair 2 Rep	Not listed	48 V; 15 Ah
Solo	Not listed	48 V; 12.8 Ah

The listed input and output ratings for each charger are indexed in Table 3. For Pairs 1 and 2, Exponent did not analyze compatibility between OEM and Rep chargers and their packs.

Table 3. Chargers tested

Charger	Input Rating	Output Rating
Pair 1 OEM	100 V – 240 V, 50/60 Hz, 2.5 A (max)	54.6 V – 3.0 A
Pair 1 Rep	110 V – 245 V, 50/60 Hz, 3.0 A (max)	54.6 V – 3.0 A
Pair 2 OEM	100 V – 240 V, 50/60 Hz, 2.5 A (max)	54.6 V – 3.0 A

Charger	Input Rating	Output Rating
Pair 2 Rep	100 V – 245 V, 50/60 Hz, 2.5 A (max)	54.6 V – 2.0 A
Solo	110 V – 240 V, 50 Hz, 1.0 A (max)	54.6 V – 2.0 A

Exponent performed a visual and online search for relevant certifications of the packs and chargers. Both OEM battery packs are represented as certified to UL 2849 as part of an e-bike system, although Exponent was unable to confirm the certification for Pair 2 OEM. None of the other three packs (Pair 1 Rep, Pair 2 Rep, and Solo) were found to have any UL-relevant certification through product markings and online research.

Some chargers supplied with the battery packs exhibited markings indicating testing to an industry standard. UL 2849 Section 23.1 requires the chargers used to be compliant with one of the following:

- UL 1012, and CSA C22.2 No. 107.1;
- UL 1310 and CSA C22.2 No. 223;
- UL 60950-1/CSA C22.2 No. 60950-1, along with the relevant Part 2 Standard as applicable; or
- UL 62368-1/CSA C22.2 No. 62368-1.

A summary of the relevant certifications and markings for the tested components can be found in Table 4.

Table 4. Component Certifications

Component	Certification	Component	Relevant Certification and Markings[7]
Pair 1 OEM – Pack	UL 2849	**Pair 1 OEM – Charger**	UL 1012, UL 1310
Pair 1 Rep – Pack	-	**Pair 1 Rep – Charger**	UL 1012
Pair 2 OEM – Pack	UL 2271 and 2849	**Pair 2 OEM – Charger**	UL 1012
Pair 2 Rep – Pack	-	**Pair 2 Rep – Charger**	-

7 Charger UL certifications were verified at https://iq.ulprospector.com/en.

Component	Certification	Component	Relevant Certification and Markings[7]
Solo – Pack	-	**Solo – Charger**	GB4706-1-2005, GB4706-18-2014, QBT2947-1-2008

A.1 Pair 1 Overview

The Pair 1 battery packs chosen were intended for a commercially-available e-bike. The e-bike, which includes the OEM battery pack, has been certified to industry standard UL 2849. The replacement battery pack (Pair 1 Rep – Pack) was reported as compatible with the e-bike that uses Pair 1 OEM, according to vendor's website, and was not reported as certified to any UL standard.

Each battery pack was supplied with a charger. The OEM and Rep chargers were marked as having UL certification (see Table 4).

Exponent also procured a new e-bike for Pair 1 OEM after it was determined to be required for testing (see Section B – Pack Construction and Safety Evaluation).

Figure 6. Pair 1 OEM – Pack.

Figure 7. Pair 1 Rep – Pack.

Figure 8. Pair 1 OEM – Charger.

Figure 9. Pair 1 Rep – Charger.

A.2 Pair 2 Overview

The Pair 2 battery packs chosen were intended for a down-tube e-bike and were compatible with multiple versions of the e-bike. The e-bike, which includes the OEM battery pack, is reported as being certified to industry standard UL 2849. The replacement battery pack is thought to be compatible with the e-bike above based on the form factor, electrical connections, specification sheets, and markings. For the markings, the Pair 2 batteries each have logo markings on the pack exterior indicating that they are both the same types that are typically used for down-tube arrangements. The Pair 2 replacement battery packs are available for purchase at common online marketplaces.

Each battery pack was supplied with a charger. The OEM charger was marked as having UL certification (see Table 4).

Figure 10. Pair 2 OEM – Pack.

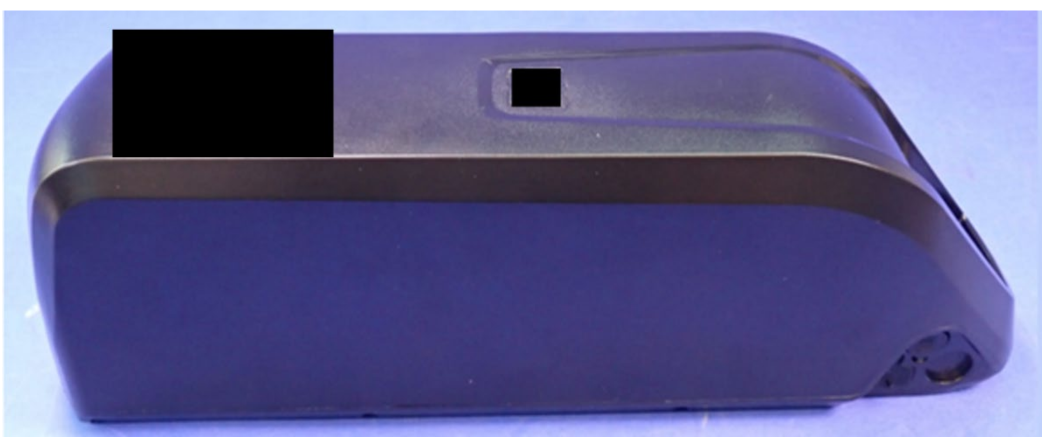


Figure 11. Pair 2 Rep – Pack.

Figure 12. Pair 2 OEM – Charger.

Figure 13. Pair 2 Rep – Charger.

A.3 Solo Overview

The Solo battery pack chosen was a generic e-bike battery intended to be used for many models of e-bikes, including folding e-bikes. The battery packs were provided with a key to turn it on/off, as well as a charger. The pack did not have any UL certifications listed. The charger supplied with the packs did not have any UL certifications listed but did have several GB certifications listed (see Table 4).

Figure 14. Solo – Pack.

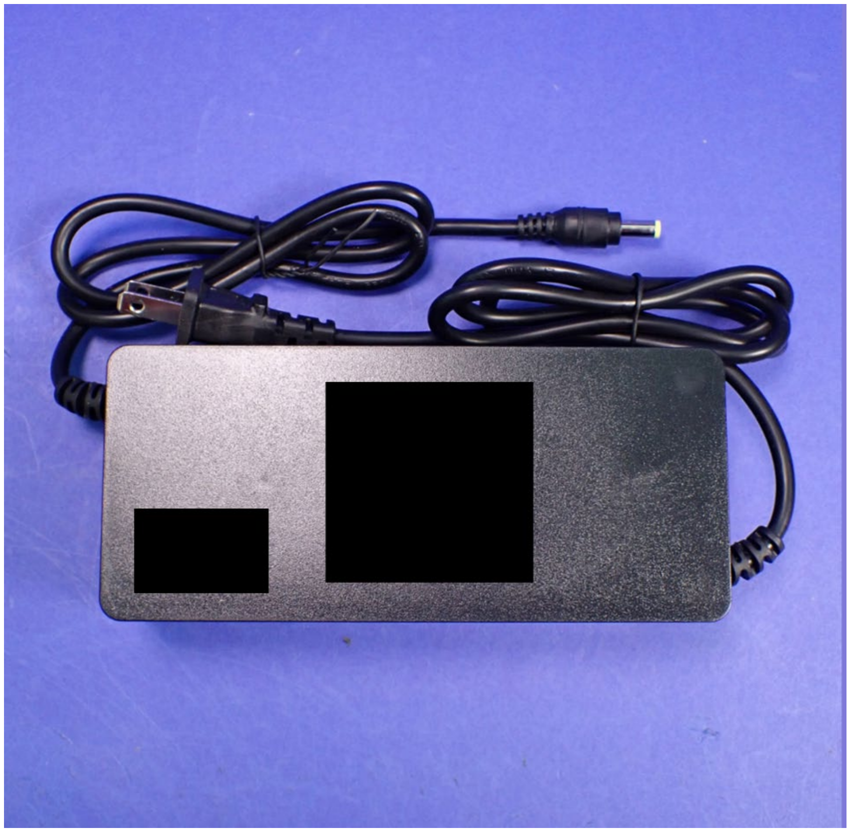


Figure 15. Solo – Charger.

B. Pack Construction and Safety Evaluation

B.1 Introduction

As part of this task, Exponent evaluated the construction quality and safety features of each battery pack. The information obtained in this section served two main purposes. The first purpose was to obtain information about the functionality of each pack to help interpret the results from Sections C through F. The second purpose was to understand how these products compare with state-of-the-art battery packs and find common weaknesses, shortcomings, or limitations to their construction and functionality with regard to the impact on safety.

B.2 Pack Construction

B.2.1 Test Overview

The battery packs were inspected with specific focus on the construction such as the enclosure, connectors, and respective chargers, as well as labeling, certifications, and specifications included on the external surfaces of the packs. Once the external state of each pack was documented, the battery packs were also disassembled to inspect the internal construction of the packs, their safety infrastructure, and overall build quality. During disassembly, several features were noted and documented, such as the connectors or any other vulnerable areas that may lead to moisture or dust ingress, printed circuit board (PCB) placement on packs, insulation scheme, the cell stack, and cable routing for cell group monitoring.

The deconstruction also focused on the quality of soldering within the pack, cleanliness of the PCBs, quality of the tab welds on the cells, busbar routing, and an overview of the protection circuitry. Since these packs were purchased off-the-shelf, the schematics and bills of material (BOM) were not available for review. Disassembly also allowed for visual verification of the presence of safety components such as fuses and temperature sensors. After each pack was documented and disassembled, five cells were extracted for further inspection and disassembly.

The following section summarizes some of the observations made during the inspections of all five battery packs. Representative images of some of the observations made appear in the Appendices at the end of the report.

B.2.2 Results

Table 5. Construction quality of Pair 1 OEM – Pack

Construction	IP Rating: IPX4
	Gaskets present on both sides of pack enclosure; No gaskets or sealing mechanisms observed for screws on both ends of the enclosure.
	Potting material present around the pack terminals at the connector; Positive and negative terminals have heat shrinks on the cables.
	No visual battery state-of-charge indicator present on the pack.
PCBs	Battery PCB conformally coated.
	One temperature sensor present on the PCB in the vicinity of MOSFETs.
	No signs of flux, solder splatter or contaminants on the PCB.
Cable Management	Low power and high power cable routed separately.
	Voltage sense cables and temperature sensor cables are insulated from the cell stack and routed in a controlled manner to the PCB.
Cell Stack	Insulation, white potting material, and Kapton tapes present on the cell stack.
	Signs of overheating observed on some tab welds on cell cans.[8]
	PCB insulated from the cell stack.
Safety Components	Four temperature sensors on the cell stack and one on the PCB.
	Low voltage circuit fuse (10A) and 3-terminal high current fuse (30A) present.
	Moisture indicator paper present towards one end of the cell stack. However, no correlation between the paper and the pack BMU was found.[9]
	The BMU appears to have cell balancing infrastructure, it is not known if this feature is activated in the pack.

[8] Figure B - 1

[9] Figure B - 2

Table 6. Construction quality of Pair 1 Rep – Pack

Construction	No gaskets or sealing mechanism on pack enclosure and screws.
	Potting material present around the pack terminals at the connector; Positive and negative terminals have heat shrinks on the cables.
	SOC indicator has openings that are covered only with a plastic sheet held in place with an adhesive. No gasket or seals observed around this indicator making it prone to ingress.[10]
PCBs	No conformal coating on PCBs.
	No temperature sensor on the PCB.
	Evidence of solder splatter, contaminants, and flux observed on all PCBs.[11]
Cable Management	Cables and sense wires not properly insulated from the cell stack.
	Main positive and negative terminals potted near the connector.
Cell Stack	Sense wires connections covered with insulation paper and Kapton tape.
	Signs of overheating observed on some tab welds on cell cans.[12]
	PCB insulated from the cell stack.
	Inconsistent soldering and flux residue observed at the sense lines connections.[13]
Safety Components	Two temperature sensors on the cell stack.
	Input fuse (10 A) and output high current fuse (30 A) present.
	The BMU appears to have cell-balancing infrastructure, it is not known if this feature is activated in the pack.

[10] Figure B - 4

[11] Figure B - 5

[12] Figure B - 3

[13] Figure B - 6

Table 7. Construction quality of Pair 2 OEM – Pack

Construction	No gaskets or sealing mechanism on pack enclosure and screws.
	Potting material present around the pack terminals at the connector; Positive and negative terminals have heat shrinks on the cables
	SOC indicator has openings that are covered only with a plastic sheet held in place with an adhesive. No gasket or seals observed around this indicator making it prone to ingress.
	No seal or gasket on charge and discharge ports on the pack enclosure.
PCBs	No conformal coating on PCBs.
	No temperature sensor on the PCB.
	Evidence of solder splatter, contaminants and flux observed on all PCBs.[14]
Cable Management	Cables appear to be hand-soldered on to the PCB and the cell tabs.
	Main positive and negative terminals potted near the connector.
	Cables and sense wires not entirely insulated from the cell stack and routed together to the main PCB.
Cell Stack	Sense wire connections covered in some places with insulation paper and Kapton tape.
	Signs of overheating observed on some tab welds on cell cans.[15]
	PCB insulated from the cell stack.
	Inconsistent soldering and flux residue observed at the sense lines connections.
Safety Components	One temperature sensor on the cell stack.
	Output high current fuse (45 A) present.
	The BMU appears to have cell balancing infrastructure, it is not known if this feature is activated in the pack.

[14] Figure B - 8

[15] Figure B - 7

Table 8. Construction quality of Pair 2 Rep – Pack

Construction	No gaskets or sealing mechanism on pack enclosure and screws.
	No seal or gasket on charge and discharge ports on the pack enclosure.
	SOC indicator has openings that are covered only with a plastic sheet held in place with an adhesive. No gasket or seals observed around this indicator making it prone to ingress.[16]
PCBs	The main control PCB is partially conformally coated.
	There is one temperature sensor on the main PCB.
	Evidence of solder splatter, contaminants and flux observed on all PCBs.
Cable Management	Cables appear to be hand-soldered on to the PCB and the cell tabs.
	Sense wires insulated from the cell stack with a paper.
Cell Stack	Sense wire connections covered in some places with insulation paper and Kapton tape.
	Signs of overheating observed on some tab welds on cell cans.[17]
	PCB insulated from the cell stack.
	Inconsistent soldering and flux residue observed at the sense lines connections.
Safety Components	One temperature sensor present on the PCB, no temperature sensors on the cell stack.
	No fuses were observed based on visual inspection of the pack.
	The BMU appears to have cell balancing infrastructure, it is not known if this feature is activated in the pack.

[16] Figure B - 10

[17] Figure B - 9

Table 9. Construction quality of Solo – Pack

Construction	Pack enclosed in a metal casing with no additional gasket or sealing mechanism around the enclosure or around the screws.
	A mechanical connection via a key is used to enable the pack output.
	Solder/connection quality of positive and negative terminals
PCBs	Conformal coating observed in areas populated by components.
	No temperature sensor on PCB.
	Evidence of solder splatter, contaminants and flux observed on PCB.
Cable Management	Power terminals and sense wire terminals covered with potting/tape for insulation.
	Sharp cell tabs in vicinity of cables.[18]
	Sense wires insulated from the cell stack with a tape.
Cell Stack	Cell stack encompassed in an insulation.
	Signs of overheating observed on some tab welds on cell cans.[19]
	PCB insulated from the cell stack.
Safety Components	One temperature sensor on cell stack.
	No fuses were observed based on visual inspection of the pack.
	The BMU appears to have cell balancing infrastructure, it is not known if this feature is activated in the pack.

[18] Figure B - 11

[19] Figure B - 12

B.2.3 Discussion

The inspected battery packs had commonalities in terms of some of the construction features. Although the cell stack architecture and placement of circuit boards varied to a certain degree, based on number of cells within the pack and the cell connection scheme (series-parallel architecture), they all exhibited design deficiencies listed in the tables above that are critical to the safety of the battery packs.

Some common positive design aspects included:

- The cell stack was insulated from the pack electronics
- At least one temperature sensor was on the cell stack
- Voltage sense lines were insulated and routed from the cell groups to the BMU
- Over-current and overcharge protection

Some common weaknesses observed in the pack designs included:

- Lack of adequate sealing along the enclosures and charge/discharge ports of the battery packs, making them prone to moisture and dust ingress
- Evidence of the presence of solder splatter, flux, debris, and contaminants on the circuit boards which may imply a poor manufacturing process
- Signs of poor resistance welding quality on the cell tabs
- Signs of inconsistent soldering of the sense lines on the cell group tabs

Poorly sealed pack enclosures provide avenues for moisture, dust, and contaminants to enter the pack. Lack of proper conformal coating on the circuit boards can result in these contaminants causing faults such as short-circuits or low resistance faults between opposite polarity connections. Such faults, in worst cases, can lead to a propagating circuit board failure, and in turn, potential cell thermal runaway.

Signs of inconsistent and uncontrolled welding of current collector tabs to the cells was observed in most of the packs inspected. This shows lack of quality checks in the resistance welding processes and can result in the cells themselves being exposed to high heat and thermal damage. Prolonged exposure to heat or an over-heating induced perforation of a cell can may lead to latent faults within the cell.

B.3 Pack-level Testing

B.3.1 Testing Overview

Each of the five battery packs were put through a series of five separate tests to characterize and outline the behavior and safety features in each pack. For each of the following tests, the pack was instrumented to record pack voltage, current, ambient temperature, and external pack temperature. Each pack was discharged at 0.5 C-rate.[20] The packs were then charged using the charger supplied by the manufacturer.

The packs were tested to characterize standard charge and discharge with a constant current load. The packs were also tested for evaluating protection against overcharging, a short-circuit condition, and determining allowable temperature ranges while charging in a thermal chamber (0 °C – 65 °C).

B.3.2 Results Overview

Table 10 includes an overview of the test results for all five packs. The following sections describe the tests and the results for each of the packs in detail.

[20] The "C-rate" of a battery refers to the rate of time it takes to charge or discharge. The "C-rate" is a function of an individual pack's capacity and varies from pack to pack. In the absence of an appropriate load (e-bike), by discharging at rate, an equitable comparison can be made across all the packs.

Table 10. Summary of Section B.3 pack testing

Pack	Charge Characterization	Discharge Characterization	Overcharge	Short-Circuit	Measured Allowable Temperatures During Charging[21]
Pair 1 OEM	Rated current: 3 A Fully charged voltage: 54.6 V Charge current cut-off: 0.16 A	Overdischarge voltage cut-off: 35.1 V	Activation of overcharge protection: 55.6 V	Pack shuts off, no noticeable damage	22 °C to 64 °C
Pair 1 Rep	Rated current: 3 A Fully charged voltage: 54.6 V Charge current cut-off: 0.36 A	Overdischarge voltage cut-off: 35.9 V	Activation of overcharge protection: 55.6 V	Pack shuts off, no noticeable damage	22 °C to 58 °C
Pair 2 OEM	Rated current: 3 A Fully charged voltage: 54.6 V Charge current cut-off: 0.16 A	Overdischarge voltage cut-off: 35.8 V	Activation of overcharge protection: 56.0 V	Pack shuts off, no noticeable damage	17 °C to 63 °C
Pair 2 Rep	Rated current: 2 A Fully charged voltage: 54.6 V Charge current cut-off: N/A	Overdischarge voltage cut-off: 39.1 V	Activation of overcharge protection: 55.6 V	Pack shuts off, no noticeable damage	N/A
Solo	Rated current: 2 A Fully charged voltage: 54.6 V Charge current cut-off: 0.22 A	Overdischarge voltage cut-off: 37.1 V	Activation of overcharge protection: 55.8 V	Pack shuts off, no noticeable damage	63 °C (No lower threshold)

[21] The thermocouple was placed on the exterior surface of the pack for this test. The temperatures recorded during this test may not be representative of the actual cell temperatures enclosed within the pack. Since we did not have access to the schematics or specifications for these battery packs, the allowable operating temperature range could not be verified.

B.3.3 Charge Characterization

B.3.3.1 Results

Results for this test are summarized in Table 10.

- **Pair 1 OEM –** A fully discharged pack was charged with the specified charger. The charge cycle was completed in approximately 5 hours. The pack followed a CC-CV profile with the upper voltage limit of 54.4 V and minimum charge current cut-off of 0.16 A (see Figure B - 13).

- **Pair 1 Rep –** A fully discharged pack was charged with the specified charger. The charge cycle was completed in approximately 4 hours 50 minutes. The pack followed a CC-CV profile with the upper voltage limit of 54.6 V and minimum charge current cut-off of 0.36 A (see Figure B - 14).

- **Pair 2 OEM –** A fully discharged pack was charged with the specified charger. The charge cycle was completed in approximately 5 hours. The pack followed a CC-CV profile with the upper voltage limit of 54.6 V and minimum charge current cut-off of 0.16 A (see Figure B - 15).

- **Pair 2 Rep –** A fully discharged pack was charged with the specified charger. The pack followed a CC-CV profile with the upper voltage limit of 54.6 V. The CC-charge cycle was completed in approximately 7 hours and 30 minutes However, no charge current cut-off during CV-charging period was observed and hence, the charging was terminated manually at CV current of 0.01 A (see Figure B - 16).

- **Solo –** A fully discharged pack was charged with the specified charger. The pack followed a CC-CV profile with the upper voltage limit of 54.6 V. The charge cycle was completed in approximately 7 hours. The pack followed a CC-CV profile with the upper voltage limit of 54.6 V and minimum charge current cut-off of 0.22 A (see Figure B - 17).

Values of cell equivalent CV mode charging current cut-off were calculated using the last recorded charging current in the tested packs divided by the number of cells in parallel. Their values can be found in Table 11 alongside the cell specifications sheet values (further details of cell specifications can be found in Section B.4.1).

Table 11. Cell equivalent CV mode Charging Current Cut-off

Pack	Pack Charging Current Cut-off (mA)	Cell Equivalent Charging Current Cut-off (mA)	Cell Specifications Charging Current Cut-off at 4.2 V (mA)
Pair 1 OEM	160	40	50
Pair 1 Rep	360	90	n/a
Pair 2 OEM	160	40	50
Pair 2 Rep	<10	<1.7	52
Solo	220	55	61

B.3.3.2 Discussion

Of particular concern is the apparent lack of charging cut-off in the Pair 2 Rep sample in the CV stage of the charge, resulting in float charging. As described in Scenario 4 in the E-bike Charging Overview Section, lithium-ion batteries are generally incompatible with float charging and can result in their overcharge. With extended use of the Pair 2 Rep – Pack with the Pair 2 Rep – Charger, the pack is susceptible to being overcharged and could present an elevated safety risk. Exponent did not evaluate the long-term hazards associated with Pair 2 Rep – Pack.

The CV current cut-off values recorded in the packs were in-line with the cell specification values. The equipment used for current measurements made by Exponent is limited by its resolution. Given that the measured values of "Cell Equivalent Charging Current Cut-off" are consistently lower than the specification values (except for Pair 2 Rep – Pack), it is reasonable to assume that the differences are due to measurement error rather than design choices.

B.3.4 Discharge Characterization

B.3.4.1 Results

Results for this test are summarized in Table 10.

- **Pair 1 OEM –** A partially charged pack was discharged with a constant current of 5 A using an external DC load. The pack is equipped with overdischarge voltage protection, and the discharge current stopped flowing once the pack voltage reached 35.1 V (see Figure B - 18).

- **Pair 1 Rep –** A partially charged pack was discharged with a constant current of 5 A using an external DC load. The pack is equipped with overdischarge voltage protection, and the discharge current stopped flowing once the pack voltage reached 35.9 V (see Figure B - 19).

- **Pair 2 OEM –** A partially charged pack was discharged with a constant current of 5 A using an external DC load. The pack is equipped with overdischarge voltage protection, and the discharge current stopped flowing once the pack voltage reached 35.8 V (see Figure B - 20).

- **Pair 2 Rep –** A partially charged pack was discharged with a constant current of 5 A using an external DC load. The pack is equipped with overdischarge voltage protection, and the discharge current stopped flowing once the pack voltage reached 39.1 V (see Figure B - 21).

- **Solo –** A partially charged pack was discharged with a constant current of 5 A using an external DC load. The pack is equipped with overdischarge voltage protection, and the discharge current stopped flowing once the pack voltage reached 37.1 V (see Figure B - 22).

B.3.4.2 Discussion

All the packs appeared to have overdischarge voltage protection which ranges from approximately 35 V to 39 V. From the cell specifications provided, only Pair 2 Rep – Pack cells have a discharge limit of 2.75 V (35.75 V for pack). The cells from the other four packs can be discharged to 2.5 V (32.5 V for pack). The results indicate that the overdischarge voltage protection of all five packs satisfied the discharge voltage limits of the respective cells.

B.3.5 Pack Overcharge Test

B.3.5.1 Results

Results for this test are summarized in Table 10.

- **Pair 1 OEM –** A fully discharged pack was charged using an external power supply current limited to the rated charge current (3 A). The pack is equipped with overcharge protection and the charge current stopped flowing once the pack voltage reached 55.6 V (see Figure B - 23).

- **Pair 1 Rep –** A fully discharged pack was charged using an external power supply current limited to the rated charge current (3 A). The pack is equipped with overcharge protection and the charge current stopped flowing once the pack voltage reached 55.6 V (see Figure B - 24).

- **Pair 2 OEM –** A fully discharged pack was charged using an external power supply current limited to the rated charge current (3 A). The pack is equipped with overcharge protection and the charge current stopped flowing once the pack voltage reached 56.0 V (see Figure B - 25).

- **Pair 2 Rep –** A fully discharged pack was charged using an external power supply current limited to the rated charge current (2 A). The pack is equipped with overcharge protection and the charge current stopped flowing once the pack voltage reached 55.6 V (see Figure B - 26).

- **Solo –** A fully charged pack was charged using an external power supply current limited to the rated charge current (2 A). The pack is equipped with overcharge protection and the charge current stopped flowing once the pack voltage reached 55.8 V (see Figure B - 27).

B.3.5.2 Discussion

Each pack type was equipped with overcharge voltage protection. The setpoint values are in close proximity to the nominal upper voltage limit of the pack during normal use, in keeping with industry best practices.

B.3.6 Allowable Charge Temperature Test

B.3.6.1 Results

Results for this test are summarized in Table 10. The designated charger used for these tests was placed outside the environmental chamber.

- **Pair 1 OEM –** A fully discharged pack was charged using its designated charger inside an environmental chamber to evaluate the lower and upper charging temperature thresholds (if any) that may be programmed in the battery pack. The initial temperature of the chamber was approximately -10 ºC. The pack started charging when the pack exterior temperature reached 22 ºC and stopped when its temperature reached 64 ºC (see Figure B - 28).

- **Pair 1 Rep –** A fully discharged pack was charged using its designated charger inside an environmental chamber to evaluate the lower and upper charging temperature thresholds (if any) that may be programmed in the battery pack. The initial temperature of the chamber was approximately -10 ºC. The pack started charging when the pack exterior temperature reached 22 ºC and stopped charging when its temperature reached 58 ºC (see Figure B - 29).

- **Pair 2 OEM –** A fully discharged pack was charged using its designated charger inside an environmental chamber to evaluate the lower and upper charging temperature thresholds (if any) that may be programmed in the battery pack. The initial temperature of the chamber was approximately -10 ºC. The pack started charging when the pack exterior temperature reached 17 ºC and stopped charging when its temperature reached 63 ºC (see Figure B - 30).

- **Pair 2 Rep –** A fully discharged pack was charged using its designated charger inside an environmental chamber to evaluate the lower and upper charging temperature thresholds (if any) that may be programmed in the battery pack. The initial temperature of the chamber was approximately -10 ºC. The pack started charging from the beginning of the test and continued to do so as the exterior temperature increased to 65 ºC (see Figure B - 31). Hence, a distinct lower temperature threshold for charging this pack could not be determined.

- **Solo –** A fully discharged pack was charged using its designated charger inside an environmental chamber to evaluate the lower and upper charging temperature thresholds (if any) that may be programmed in the battery pack. The initial temperature of the chamber was approximately -10 ºC. The pack started charging from the beginning of the test and stopped charging when its exterior temperature reached 64 ºC (see Figure B - 32). Hence, the lower temperature limit for charging this pack (below -10 ºC) could not be determined.

B.3.6.2 Discussion

The main purpose of this test was to understand if the packs had functionality included to limit charging to a particular temperature range. Pair 1 OEM – Pack, Pair 1 Rep – Pack, and Pair 2 OEM – Pack have the ability to limit the charge at both low and high temperature ranges. The Solo – Pack component was only observed to have a limit at an elevated temperature, while the Pair 2 Rep – Pack did not prevent charging within any of the tested temperatures.

The exact values recorded should not be compared to any particular specifications of the pack or cells. The temperature logged for these tests was on the pack exterior, and not at a location either on the cells or at the circuit board. Since the testing was performed starting at a low environmental temperature followed by an increasing temperature ramp at a rate of approximately 2 °C per minute, there is thought to be a temperature gradient between the pack exterior and the internal components. Further tests on the pack functionality to allow charging at cold/hot climate were conducted and are discussed in Section C and D.

B.3.7 Pack Short-Circuit Test

B.3.7.1 Results

Results for this test are summarized in Table 10.

- **Pair 1 OEM –** A fully charged pack was subjected to a short-circuit test such that the pack terminals were shorted using an in-line DC contactor. The pack immediately terminated the short-circuit current and no damage or change in temperature was observed during or after of the test (see Figure B - 33). The pack appears to have short-circuit protection.

- **Pair 1 Rep –** A fully charged pack was subjected to a short-circuit test such that the pack terminals were shorted using an in-line DC contactor. The pack immediately terminated the short-circuit current and no damage or change in temperature was observed during or after of the test (see Figure B - 34). The pack appears to have short-circuit protection.

- **Pair 2 OEM –** A fully charged pack was subjected to a short-circuit test such that the pack terminals were shorted using an in-line DC contactor. The pack immediately terminated the short-circuit current and no damage or change in temperature was observed during or after of the test (see Figure B - 35). The pack appears to have short-circuit protection.

- **Pair 2 Rep –** A fully charged pack was subjected to a short-circuit test such that the pack terminals were shorted using an in-line DC contactor. The pack immediately terminated the short-circuit current and no damage or change in temperature was observed during or after of the test (see Figure B - 36). The pack appears to have short-circuit protection.

- **Solo –** A fully charged pack was subjected to a short-circuit test such that the pack terminals were shorted using an in-line DC contactor. The pack immediately terminated the short-circuit current and no damage or change in temperature was observed during or after of the test (see Figure B - 37). The pack appears to have short-circuit protection.

B.3.7.2 Discussion

All five pack types were observed to include a short-circuit protection safety component in the event of a failure that results in a rapid discharge, in keeping with industry best practices. The short-circuit current was interrupted by the packs prior to any visible damage.

B.4 Cell-level Testing

The cells contained in the battery packs were analyzed for their construction quality against industry best practice and Exponent's experience.

B.4.1 Cell Specifications

The technical data sheets of the cells for each pack were acquired by conducting an online search of the cell model number indicated on the wrappers. Exponent has assumed that the cells in the packs are authentic (i.e., not counterfeit). A summary of the cell specifications can be found in Table 12. All cells are manufactured by well-known cell manufacturers.

All cells have a nominal capacity of 3.0 Ah to 3.5 Ah except for Pair 2 Rep – Pack cells which have a nominal capacity of 2.6 Ah. This lower capacity for Pair 2 Rep – Pack cells is due to the 13s6p configuration as opposed to the 13s4p configuration of the corresponding OEM pack (Pair 2 OEM – Pack). The two extra cells in parallel are needed to match the capacity between the OEM and replacement pack.

All cells have similar discharge/charge operating temperature cut-offs and short- to medium-term shelf storage requirements. The voltage cut-offs of all cells are within the range of the corresponding battery pack requirement. For example, assuming all cells are balanced, thirteen cells connected in series can provide approximately 39 to 54 V, depending on the state of charge. These values are within the pack specifications which state an upper limit of 54.6 V. Based on the cell specifications and pack rating, the series-parallel construction of all packs and the pack rating are consistent.

Table 12. Cell specifications as reported by cell data sheets sourced from multiple resources.

Pack	Capacity (mAh)	Voltage Limits (V)	Maximum Current (A);	Operating Temperature (°C)	Storage Temperature (°C)	CC-CV current cut-offs
Pair 1 OEM	Typical: 3200 Mininum: 3100	2.5 – 4.2 (±0.05)	Charge: 3.1 Discharge: 10	Charge: 0 – 45 Discharge: -20 – 60	1m: -20 – 60 3m: -20 – 45 1y: -20 – 20	0.050 A
Pair 1 Rep	Typical: 3450 Minimum: 3350	2.5 – 4.2 (±0.03)	Charge: (10-45 °C) 1.675 (0-10 °C) 0.838 Discharge: (0-40 °C) 10	Charge: 10 – 45 Discharge: -20 – 60	1m: -20 – 50 3m: -20 – 40 1y: -20 – 20	4 hours
Pair 2 OEM	Typical: 3500 Minimum: 3400	2.5 – 4.2 (±0.03)	Charge: 3.4 Discharge: 10	Charge: 0 – 45 Discharge: -20 – 60	1m: -20 – 60 3m: -20 – 45 1y: -20 – 20	0.050 A
Pair 2 Rep	Typical: 2600 Minimum: 2500	2.75 – 4.2 (±0.03)	Charge: (0-5 °C) 0.26 (5-15 °C) 0.52 (15-45 °C) 1.3 Discharge: (-20-5 °C) 1.3 (5-45 °C) 5.2 (45-60 °C) 3.9	Charge: 0 – 45 Discharge: -20 – 60	1m: -20 – 60 3m: -20 – 40 1y: -20 – 20	0.052 A
Solo	Typical: 3180 Minimum: 3030	2.5 – 4.2	Standard: 0.91 A	Charge: 10 – 45 Discharge: -20 – 60	-20 – 50	0.061 A

B.4.2 Computed Tomography X-ray Imaging

Computed tomography X-ray imaging, or CT scanning, is a non-destructive technique that allows one to assess the internal physical structure of an object by generating a three dimensional (3D) visual representation of the object's physical characteristics. When collected with sufficiently high resolution, the generated data set is an excellent way to assess the as-built condition of lithium-ion cells and to elucidate the presence of any defects or other safety risks that may have been introduced during the manufacturing process. For this work, Exponent randomly selected five (5) cells from each pack and scanned the cells using a Nikon XTH 225 ST CT instrument with a resolution, or voxel size, of approximately 45 µm.

Figure 19 shows a representative image of the positive top cap assembly of each cell type. In keeping with industry best practices, each of the cell designs contains a current interruption device (CID). The CID is a protection feature that permanently disconnects the positive terminal from the electrode assembly when an undesirable high-pressure event occurs within the cell can. Operation of the CID is irreversible and effectively opens the current conduction path, rendering the cell inoperable.[22]

If activation of the CID and interruption of the flow of current fail to stop the undesirable process (or processes) responsible for pressure increase within the cell, a properly designed CID also contains engineered features that vent the space inside the cell can to the atmosphere. Most often these venting features are in the form of a score mark or stamping that selectively thins a portion of the metal supporting the CID, making it less strong than the material around it. These venting features are usually arranged in a pattern that is concentric with the top cap assembly and are often referred to as the "burst disc." The burst disc operates by permanently opening at a pressure that is below the pressure required to rupture the can wall. This is an effective way to prevent rapid disassembly of the cell can due to over-pressurization.

[22] Mikolajczak C, Kahn M, White K, Long RT. Lithium-ion batteries hazard and use assessment. Springer Science & Business Media; 2012 Mar 23.

As can be seen in Figure 19, each of the five cell types included in this study have a CID. Additionally, each CID design contains features consistent with inclusion of a burst disc. While design of CID between cells appeared to be different, these design differences are not expected to alter the safety considerations of the cells.

In addition to the CID, the Pair 1 Rep – Pack and Solo – Pack cells contain an additional safety feature associated with the management of undesirable pressure increase due to gas generation within the cells. A mandrel, or center tube, is a feature that is included in some cell designs to prevent collapse of the electrode windings into the center of the cell. It is thought that the presence of a center tube increases the probability that gas generated far away from the CID and burst disc has a path out of the cell can. In practice, a center tube can provide additional risk abatement, but its presence is not a guarantee that pathways for gas to exit the cell will be maintained. Similarly, the absence of a center tube is not an indication of a less-safe cell. Ultimately, the design and construction of the electrode assembly, the CID, and the overall cell design and construction determines if pathways for gas escape are maintained during an over-pressurization event. Positive results from required standardized testing and analysis of the CT data presented here support that all these cells have been designed and assembled in a way that gives adequate protection from cell can rupture.

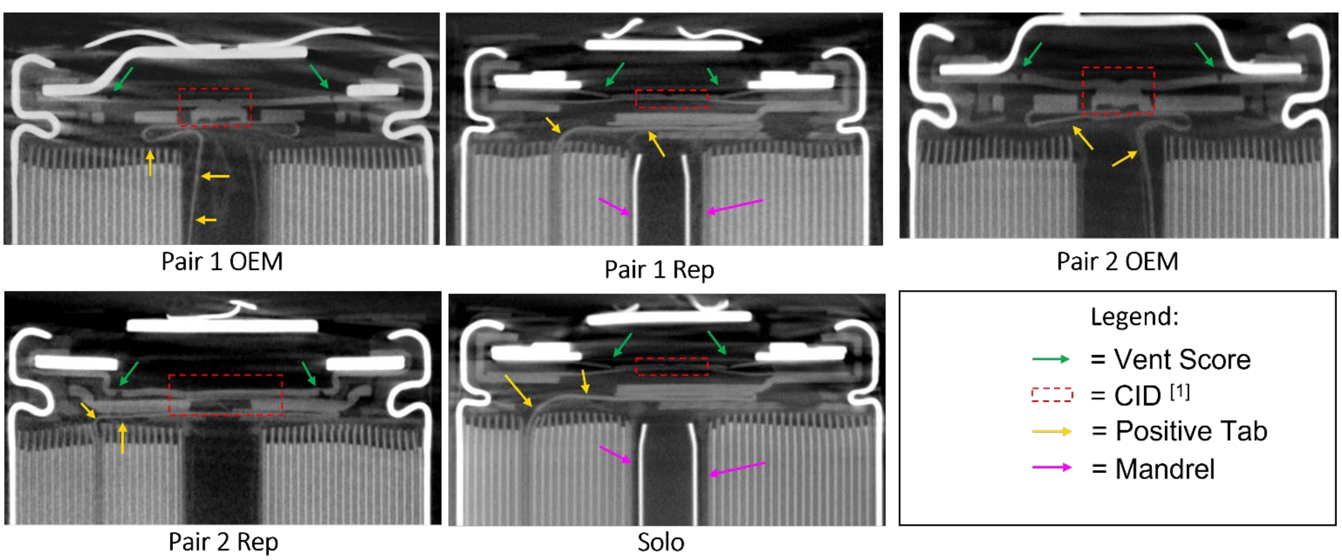


Figure 16. Cell cap construction of cells.

In terms of the cell construction, both Pair 1 OEM – Pack and Pair 2 OEM – Pack cells contained a positive cell tab connected to the innermost winding while the rest of the cells contained a tab near the mid-point of the cell windings. Internal tabs in the middle of the windings are typically preferred for higher-power applications due to better current distribution and lower internal cell impedance when charging and discharging at higher currents. This design difference, however, is not expected to alter the safety considerations of the cells. Differences in spacer thickness, position of tab welds, thickness of gaskets, and spacing of internal components were also observed among the cells, but these features are merely design choices from the manufacturer and are also not expected to alter the safety considerations of the cells.

All cells exhibited sufficient negative to positive electrode overlap (> 0.1 mm, as recommended by IEEE 1725). This overlap helps decrease the risk of metallic lithium plating at the electrode edge which can reduce cell performance and, at worst, induce a cell short circuit that results in thermal runaway. While all cells exhibited sufficient overlap, uneven or inconsistent overlap was observed in some cells from Pair 1 Rep – Pack and Solo – Pack packs. Uneven overlap could occur as a result of poor control of electrode alignment during the electrode rolling process, but no immediate safety concern is warranted if the overlap is sufficient, as is demonstrated in all the analyzed cells.

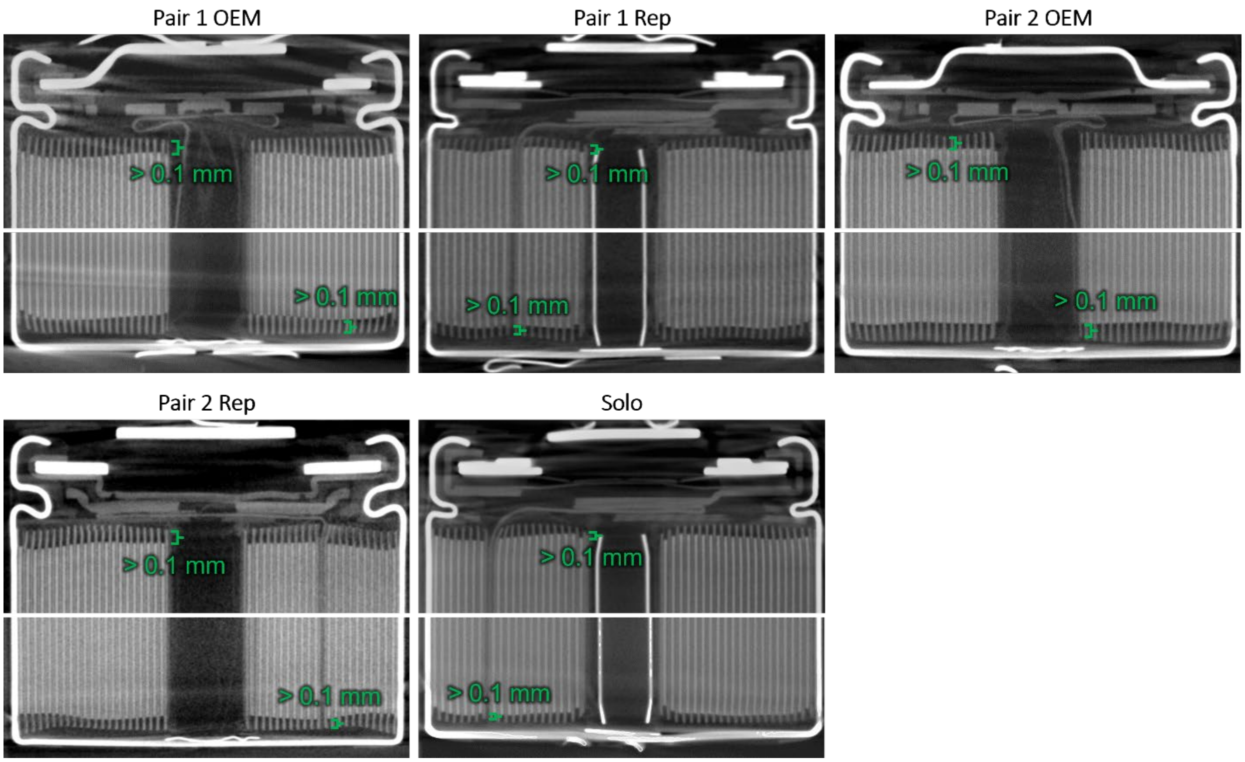


Figure 17. Negative to positive overhang measurements; the shortest overlap was chosen for measurements.

B.4.3 Cell Destructive Physical Analysis for Quality Assurance

One cell from the CT scanned set of each pack was chosen for destructive physical analysis (DPA) at 0% state-of-charge (SOC). A DPA consists of removal of the electrode windings from the cell can and subsequent examination during unrolling of the cell windings. Of primary concern is the cell construction quality and the identities, quality, and purity of the materials used in the cell. Table 13 summarizes the different materials and observations made during disassembly of each cell.

All cells used nickel-magnesium-cobalt (NMC) based particles for the positive active material except for Pair 1 Rep and Solo cells which are nickel-cobalt-aluminum (NCA) and all cells use carbon-based particles (likely graphite) as the main negative active material. These active materials are commonly used in the industry, are thermodynamically stable at the voltage windows dictated by the specifications, and are appropriate active materials from a safety perspective. Two packs (Pair 1 Rep – Pack and Pair 2 OEM – Pack) contained silicon as an additive in the negative active material. Incorporation of silicon is known to increase energy density of the cells and facilitate performance for fast charging/discharging applications. While silicon-containing anodes often suffer from faster capacity fade compared to pure graphite anodes, the inclusion of small amounts of silicon (in the case of these cells, 1% – 2%) does not impact cell safety.

As noted above in Figure 19, cells from Pair 1 OEM – Pack and Pair 2 OEM – Pack have the positive tab on the innermost winding while other packs have the positive tab in the middle of the cell windings. For tabs located where there is only one layer of separator providing insulation from the opposite electrode, as is the case for tabs placed near the middle of the electrode windings, applicable standards, such as IEEE 1725, recommend that additional insulation be used. Tabs not located at the end of the electrode (a location opposed by the same electrode) should be covered by a piece of insulating tape to decrease the likelihood of a short circuit caused by wear on the separator by the tab.

In keeping with industry best practices, the positive tabs of Pair 1 Rep – Pack, Pair 2 Rep – Pack, and Solo – Pack cells are covered with tape on both sides. Similarly, on the negative tabs, tape is applied on the inward facing surface unless the design of the negative electrode has enough length to provide an additional separator layer in between the tab and the cathode. In some cells, the tape protecting the negative tab covers the weld areas but leaves the top or bottom of the tab exposed. Protection of the weld region with tape is critical, however Exponent is not aware of a standard requiring the entire tab to be covered. Regardless, covering the entire tab with tape is not costly and provides additional protection from stress concentration at the edges of the current collection tabs.

In addition to tape applied for tab protection, all the examined cell types showed tape applied along the terminus of the active material coating to mask the region of decreased coating thickness associated with the end of the coating. This is necessary to render the region of decreased active material thickness electrochemically inactive, minimizing the risk of lithium plating in that region due to active material capacity imbalance. These observations support that all the cells that were disassembled follow tape placement best practices (Figure 21).

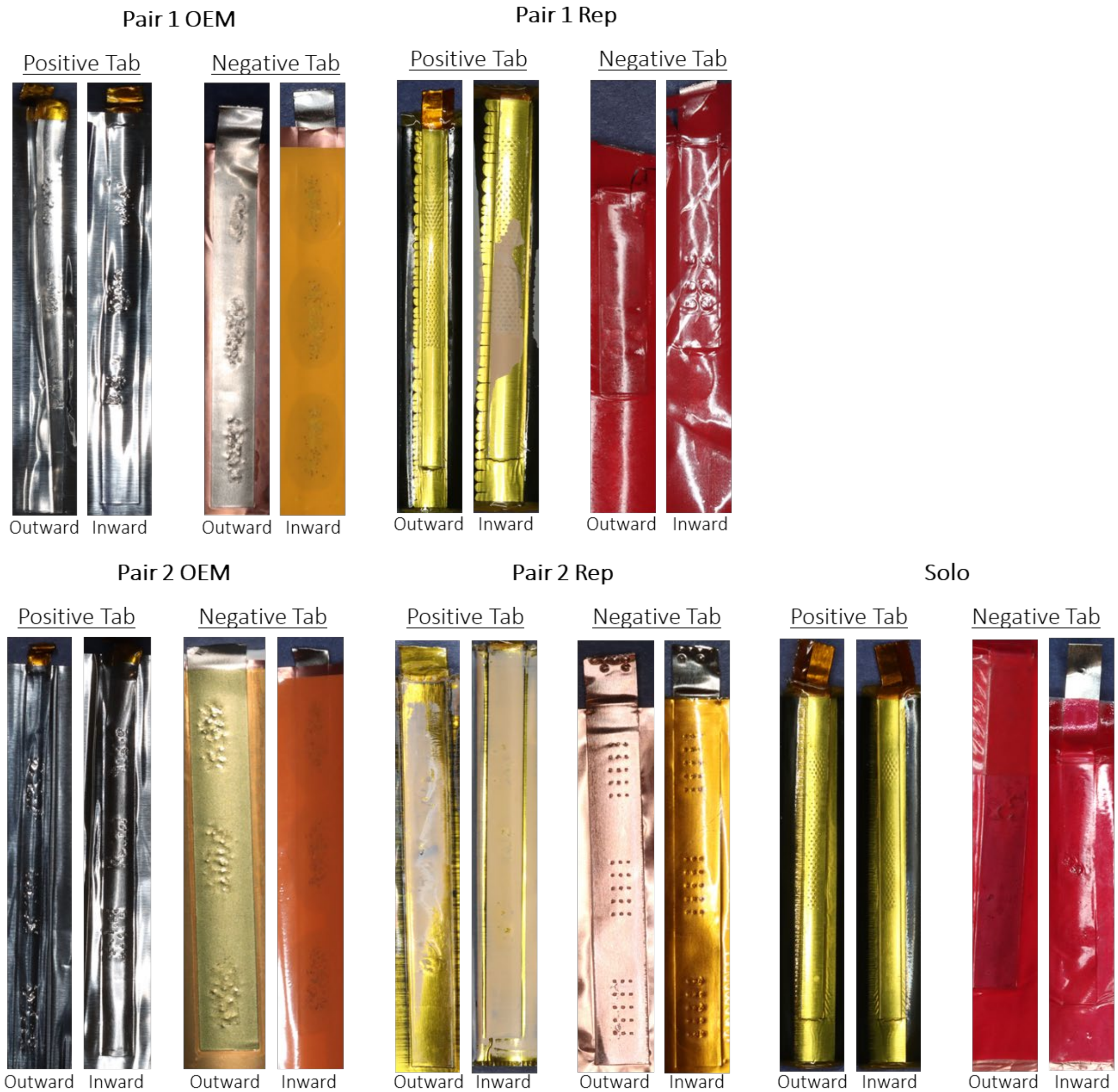


Figure 18. Tape placement on all disassembled cells.

Following best industry practices, the positive-facing separator surface of all cells examined were coated with alumina. Alumina is stable at thermal runaway temperatures and helps maintain electrode separation as the underlying polymeric separator material melts during an over-temperature event. In some rare instances, this property of the alumina coating can stop or slow down the progression of a thermal runaway event.[23] An additional, more practically useful, application for the alumina coating is to increase the resistance of the positive-facing side of the separator to oxidation induced by contact with the highly oxidizing positive electrode. This property of the alumina coating helps to extend the life of the cell by prolonging the mechanical integrity of the separator and it can provide the required improvement in oxidation resistance required by cell designs operating at higher voltages.

Despite the presence of an alumina coating (Figure 22), DPA revealed discoloration of the positive facing separator in cells harvested from Pair 1 Rep – Pack and Solo – Pack. The discoloration could be indicative of the oxidative breakdown of electrolyte or electrolyte additives at the interface of the positive electrode and separator, or it could indicate separator oxidation. The former can lead to increased resistivity and poor cell performance while the latter can do the same in addition to causing embrittlement of the polymeric material (typically polyethylene and/or polypropylene) that comprises the separator. Local embrittlement can reduce the mechanical integrity of the separator and increase the risk of separator failure and short-circuit. Additional cell cycling and chemical analysis of the discolorations would be required to determine root cause for the discoloration. These activities were beyond the scope of this work.

[23] Lee, D.W, Lee, S.H., Kim,Y.H., Oh J.M.,"Preparation of High-purity ultrafine α-Al2O3 powder and characterization of an Al2O3-coated PE separator for lithium-ion batteries". Powder Technology. 320: 125, 2017. Doi: 10.1016/j.powtec.2017.07.027

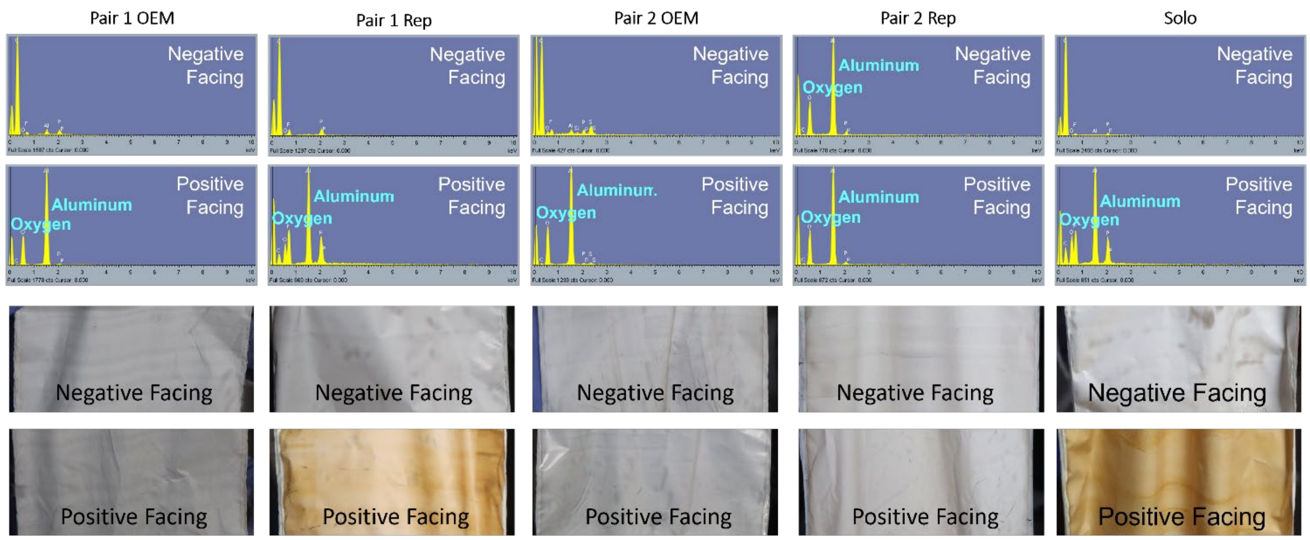


Figure 19. Separators and their composition.

Table 13. Materials used and cell observations during teardowns

Pack	Positive Active Material	Negative Active Material	Positive Facing Separator (PFS)	Negative Facing Separator (NFS)	Degradation on PFS?	Tape on Tabs?	Positive Tab Location
Pair 1 OEM	Nickel-Cobalt-Manganese (NMC)	Carbon	Alumina-coated polymer	Polymer	No	No, except negative inward	Core
Pair 1 Rep	Nickel-Cobalt-Aluminum (NCA)	Carbon doped with Silicon	Alumina-coated polymer	Polymer	Yes	Yes, on all	Middle of windings
Pair 2 OEM	Nickel-Cobalt-Manganese (NMC)	Carbon doped with Silicon	Alumina-coated polymer	Polymer	No	Yes, on all negative	Core
Pair 2 Rep	Nickel-Cobalt-Manganese (NMC)	Carbon	Alumina-coated polymer	Alumina coated polymer	No	Yes, except negative outward	Middle of windings
Solo	Nickel-Cobalt-Aluminum (NCA)	Carbon	Alumina-coated polymer	Polymer	Yes	Yes, on all	Middle of windings

B.4.4 Cell Cycling of Extracted Cells and 100% Teardowns

Table 14. Cycling conditions of cells

Pack	Charging Current [mA]	Charging CV Cut-off [mA]	Voltage Cut-offs	Discharge Current [mA]
Pair 1 OEM	750	50	Charge: 4.2 V Discharge: 3.0 V	1600
Pair 1 Rep	750	50	Charge: 4.2 V Discharge: 3.0 V	1650
Pair 2 OEM	750	50	Charge: 4.2 V Discharge: 3.0 V	1750
Pair 2 Rep	330	52	Charge: 4.2 V Discharge: 3.0 V	866.6
Solo	500	61	Charge: 4.2 V Discharge: 3.0 V	1490

One cell from each pack was chosen for short-term cycling CC-CV cycling to check for performance and cyclability of the cells. Table 14 summarizes the charging protocol conditions chosen. The charging current was selected to match the values observed in the pack level testing (i.e., intended charger output). The CV current cut-off was selected based on the pack-level cut-off current. Cut-off current was calculated by dividing the pack level current by the number of cells in parallel. A buffer was added to the calculated charging CV current to account for measurement tolerances associated with instrumentation. In the case of cells for Pair 2 Rep, where a pack current cut-off was not observed, the current was chosen based on the value specified in the cell data sheet (Table 12). The number of charge-discharge cycles was limited based on time allotted to the project. Analysis of lifetime performance of the cells is outside the scope of this report.

Figure 23 shows the discharge capacity as a function of cycle count. The cycling study demonstrated a capacity retention of at least 94% for all cells, except for Pair 2 Rep – Pack cells which exhibited a retention of 84% after 30 cycles.

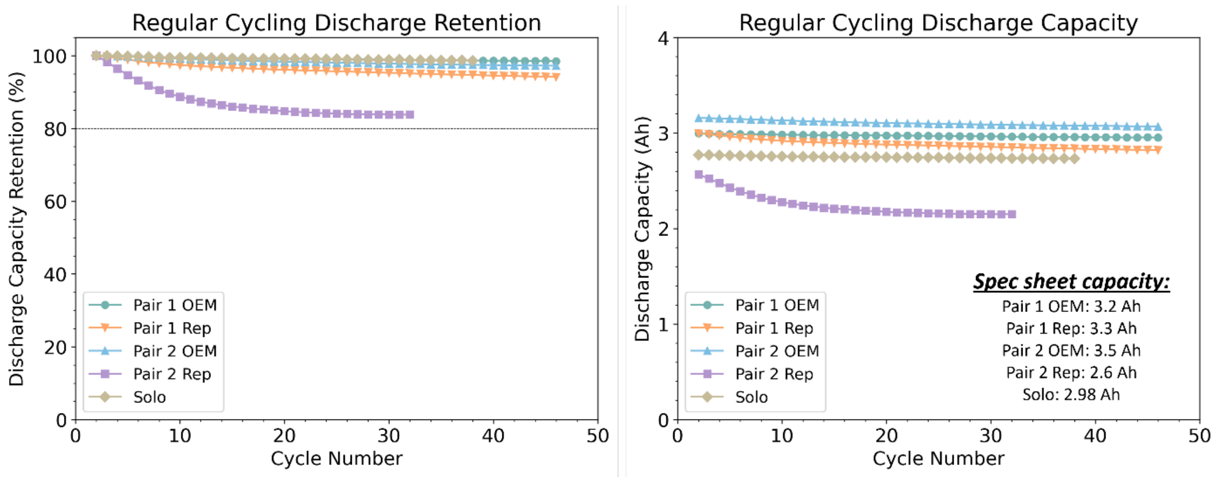


Figure 20. Cell cycling for one cell in each module.

Post-cycling DPA at 100% SOC revealed that the capacity fade observed in the Pair 2 Rep – Pack could be the result of under-lithiation of certain parts of the negative electrode (Figure 24). Fully lithiated graphite (i.e., fully charged cell) has a gold appearance as opposed to unlithiated graphite being black in appearance. Features indicating under-lithiation (darker regions) were found on both the inward- and outward-facing surfaces of the negative electrode. Outward-facing under-lithiation regions appear concentrated on the top and bottom third of the windings while inward-facing under-lithiation regions appear concentrated on the middle of the cell.

While the presence of these under-lithiated regions does not pose an immediate safety risk, the widespread nature of these regions is evidence of inhomogeneous current distributions across the surface of the negative electrode that could lead to electrolyte degradation, performance issues, and/or lithium plating and safety issues. While no deposits that pose a safety concern arose in Pair 2 Rep – Pack cells after 30 cycles, it is possible that further cycling could demonstrate latent safety risk associated with further degradation upon cycling.

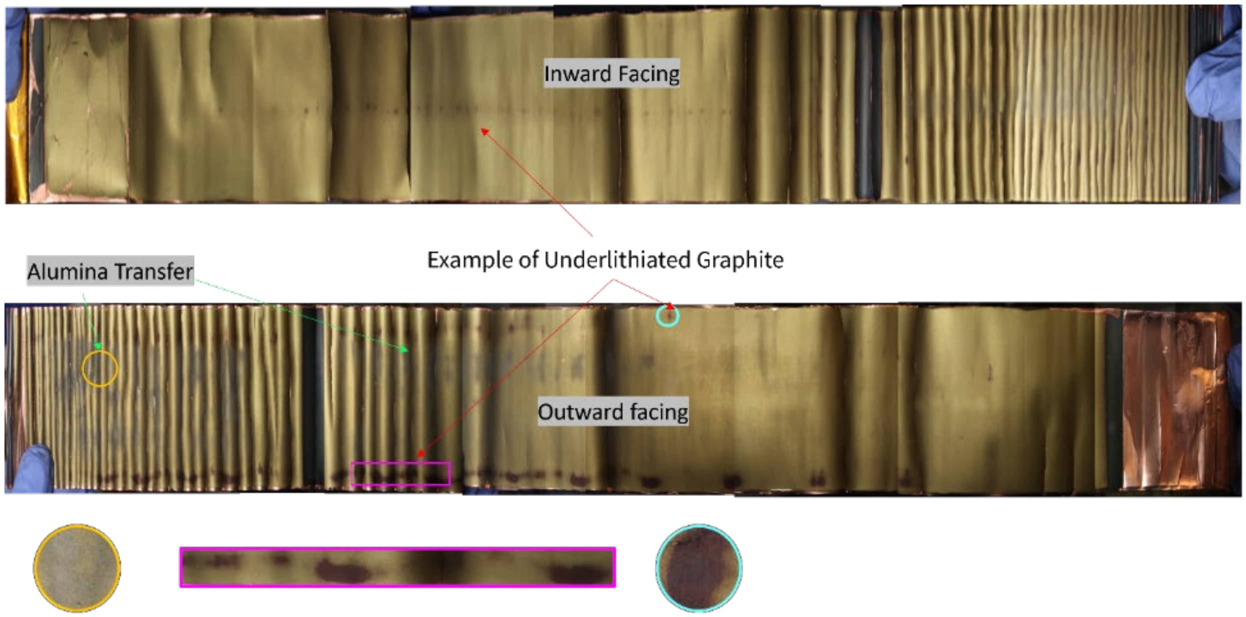


Figure 21. Pair 2 Rep – Pack negative windings at 100% SOC.

The disassembled cell from the Solo – Pack demonstrated lithium plating as evidenced by scanning electron microscopy/energy dispersive spectroscopy (SEM/EDS). Lithium plating occurs from inhomogeneity in local current distributions as a result of variations in the surface energy of the active material. This could stem from loss of contact with the electrode at local stress sites (bending regions), imbalance of active material distances, increased local decomposition of electrolyte, contaminants, or other reasons. Lithium plating was observed on a region of the outward-facing outermost region (Figure 25). This plating is characterized by dendritic lithium growth that appears as mossy regions under SEM with elevated levels of oxygen in the EDS data. EDS analysis also reveals elevated levels of fluorine and phosphorus suggesting that the lithium plating is likely accompanied by electrolyte decomposition clusters[24]. These spatially well-defined mossy regions of lithium metal are a potential safety risk due to their ability to puncture or grow through the separator and create a short. As a result,

[24] Due to its atomic structure, lithium is not detectable with conventional EDS systems, such as the system available to Exponent. The presence of elements that readily do chemistry with lithium are used as an indicator of the presence of lithium. This coupled with the characteristic morphology of the observed deposition gives confidence in the presence of lithium dendrites.

Exponent has identified the lithium plating in the post-cycle disassembly of the Solo – Pack cell to be a potential safety risk[25].

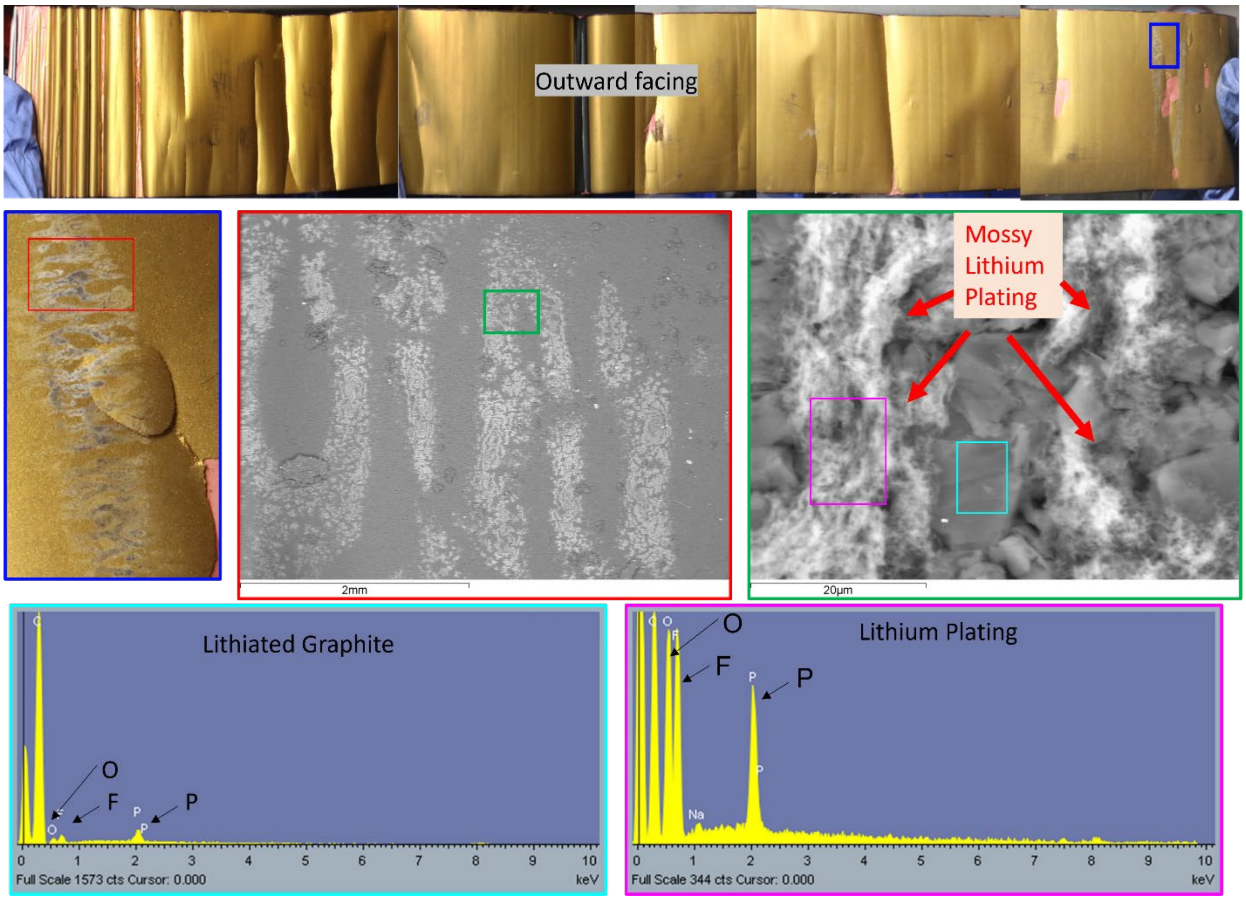


Figure 22. Evidence of lithium plating on 100% disassembled Solo – Pack cells post cycling.

B.5 Conclusion

Each pack type was evaluated for construction quality and the presence of safety components of the pack, as well as the construction quality and nominal performance of the cells included in each pack.

[25] It is important to understand that all lithium plating is undesirable because it always results in performance loss, but not all lithium plating will result in a safety concern. Because of the unpredictable nature of lithium plating and the possibility for an outcome of high severity, Exponent advocates for a conservative approach when assessing the risk associated with lithium plating.

All five packs were found to have pack construction deficiencies that increase their likelihood for a failure (Section B.2). Some of the deficiencies were common among the packs, such as a lack of adequate sealing along the enclosures and charge/discharge ports of the battery packs making them prone to moisture and dust ingress. From Exponent's experience in analyzing failed e-bike battery packs, inadequate sealing of the pack, either as construction or after mechanical damage, is a common failure mode.

The two UL 2849-rated packs (Pair 1 OEM and Pair 2 OEM) and the Pair 1 Rep – Pack largely adhered to industry best practices in the electrical and temperature tests performed in Section B.3. The other two pack types were found to have deficiencies in their ability to charge under temperature extremes. Most notably, from a safety perspective, charging the Pair 2 Rep – Pack with the intended charger appeared allow float charging during CV charging, which can result in an overcharged pack.

The cells contained in each pack type were sourced from large, well-established manufacturers and were generally constructed according to industry best practices. One cell analyzed from the Solo – Pack exhibited signs of lithium plating, which is undesirable and can lead to capacity loss and potential safety issues.[25]

C. Ambient Temperature Increasing During Charging

C.1 Introduction

Exponent performed a test on each pack, characterizing a charging scenario where the environmental temperature of the pack starts at ambient conditions and increases while the pack is still charging.

It is best practice to restrict the temperature range at which a battery pack can be charged, both at lower and upper temperature limits. The choice of temperature is primarily dictated by the temperature specifications of the cells in the pack. Cell specifications and data sheets usually include separate allowable temperature ranges for charging and discharging.

This testing evaluated the battery pack response to a 26 °C rise in environmental temperature above ambient conditions while charging. The cells in all five battery pack types have an upper temperature limit during charge of 45 °C per their specifications (see Table 12). The test procedure resulted in exposing the cells in the battery packs to temperatures above that limit while charging. Additionally, instruction provided with the Pair 1 OEM e-bikeindicate a more restrictive upper charge temperature of 40 °C for the battery pack.

C.2 Test Overview

The tests were carried out in a temperature-controlled chamber (ESPEC P-300). K-type thermocouples were used for every test to measure temperatures. A Graphtec GL-840 was used as the data logger to record the temperatures, voltages, and currents. The testing protocol is described as follows:

1. Each pack was instrumented with at least five thermocouples. Three thermocouples were placed internally (Location 1, 2, and 3) and two were placed externally (Location 4 and 5). One thermocouple (Location 1) was placed adjacent to the temperature sensor in the pack.
2. Each pack was instrumented to record pack voltage and pack current during charging.

3. Each pack was fully discharged (at 0.5 C-rate) prior to charging.
4. Each pack was charged by using the supplied (intended) charger.
5. The tests were performed in a controlled thermal chamber as follows:
    a. Each pack was soaked at 23 ºC for 30 minutes before starting the charging. The charger remained outside the chamber at ambient temperature.
    b. The thermal chamber temperature was raised to 49 ºC (± 3 ºC) at a rate of 10 ºC per hour.
    c. Once the chamber temperature reached 49 ºC, it was maintained at this temperature during the remaining period of charging.
    d. Charging was stopped when the pack was fully charged (when the charge current stopped flowing) or stopped charging at least for 60 minutes.

C.3 Results

Table 15 includes an overview of the test results for all five packs. Table 16 lists the temperatures, voltages, and currents recorded during the tests for all five packs.

Table 15. Section C test results overview

Pack	Protocol Completion Summary
Pair 1 OEM	Charging protocol performed to completion
Pair 1 Rep	Charging protocol performed to completion
Pair 2 OEM	Charging protocol interrupted when internal temperatures reached 45 °C
Pair 2 Rep	Charging protocol performed to completion
Solo	Charging protocol performed to completion

Table 16. Section C test metrics

Pack	Initial Charging Temperature (ºC)	Maximum Internal Temperature (ºC)[26]	Maximum External Temperature (ºC)[26]	Pack Voltage at 45 ºC (V)	Final Charging Voltage (V)	Temperature Specifications for Cells (ºC)	Calculated Capacity (Ah)	Rated Capacity (Ah)	Charge Current Cut-off (A)
Pair 1 OEM	23	50.8	48.4	50.7	54.6	0-45	12.9	12.8	0.16
Pair 1 Rep	23	49.5	48.7	50.6	54.6	10-45	12.6	14.0	0.36
Pair 2 OEM	23	48.6	48.3	50.6	50.6	0-45	8.8	14.0	n/a[27]
Pair 2 Rep	23	51.7	49.0	47.7	54.6	0-45	16.1	15.0	n/a[28]
Solo	23	49.3	48.0	48.1	54.6	10-45	8.8	12.8	0.22

[26] These are the maximum internal temperatures that were recorded during the test.

[27] Pack stopped charging when the internal pack temperature reached 45 ºC.

[28] Charging was stopped manually since this pack did not have a current cut-off.

C.4 Discussion

C.4.1 Pair 1 OEM

The Pair 1 OEM – Pack was charged with the specified charger. During the test, as the temperature ramped up to 49 °C, the pack completed a full charging cycle in 5 hours and 28 minutes. The charging stopped at 54.6 V when the current decreased to 0.16 A (see Figure C - 1). The pack voltage and charging current cut-off were similar to what was observed during the charge characterization test at ambient temperature in Section B.3. The internal temperature of the pack reached approximately 51 ºC during the charging, which represents the maximum cell surface temperature. This temperature exceeds the recommended maximum charging temperature as mentioned in the cell specification sheet (0 – 45 ºC).

C.4.2 Pair 1 Rep

The Pair 1 Rep – Pack was charged with the specified charger. During the test, as the temperature ramped up to 49 °C, the pack completed a full charging cycle in 4 hours and 46 minutes. The charging stopped at 54.6 V when the current decreased to 0.36 A (see Figure C - 2). The pack voltage and charging current cut-off were similar to what was observed during the charge characterization test at ambient temperature. The internal temperature of the pack reached approximately 50 ºC during the charging, which represents the maximum cell surface temperature. This temperature exceeds the recommended maximum charging temperature as mentioned in the cell specification sheet (0 – 45 ºC).

C.4.3 Pair 2 OEM

The Pair 2 OEM – Pack was charged with the specified charger. During the test, as the temperature ramped up to 49 °C, the pack did not complete a full charging cycle as the charging stopped when the internal temperatures reached approximately 45 °C. The maximum pack voltage recorded during the test was 50.6 V (3.89 V per cell group). The charging process did not restart during the remainder of the test when the chamber temperature was maintained at 49 °C. This observation supports that the BMU provides high temperature protection, which allows the pack to only charge at temperatures <45 °C (see Figure C - 3) per the cell specification sheet (0-45 ºC).

C.4.4 Pair 2 Rep

The Pair 2 Rep – Pack was charged with the specified charger. During the test, as the temperature ramped up to 49 °C, the pack completed a full charging cycle in 10 hours and 18 minutes. No cut-off for charging current was observed during the test as the current kept gradually decreasing until it was manually stopped. The final pack voltage was 54.7 V at approximately 0.03 A (see Figure C - 4). A similar charge profile was observed during the charge characterization test at ambient temperature in Section B.3. During the test, internal temperature of the pack reached approximately 52 ºC, which represents the maximum cell surface temperature. This temperature exceeds the recommended maximum charging temperature as mentioned in the cell specification sheet (0 – 45 ºC).

C.4.5 Solo

The Solo – Pack was charged with the specified charger. During the test, as the temperature ramped up to 49 °C, the pack completed a full charging cycle in 5 hours and 28 minutes. The charging stopped at 54.6 V when the current decreased to 0.22 A (see Figure C - 5). The pack voltage and charging current cut-off were similar to what was observed during the charge characterization test at ambient temperature. The internal temperature of the pack reached approximately 49 ºC during the charging, which represents the maximum cell surface temperature. This temperature exceeds the recommended maximum charging temperature as mentioned in the cell specification sheet (10 – 45 ºC).

C.4.6 Cell Evaluation

Three cells from each tested pack were evaluated for signs of degradation via CT scanning. No obvious signs of material deposits, gas formation or other forms of degradation were observed. Even though four of the five packs continued to charge above the cell specification sheet maximum temperature, damage to these cells is expected to be limited after a single charge cycle. Damage to cells charged at high temperatures can present in multiple ways, commonly in the form of electrolyte degradation and gas generation. The extent of lithium plating is dependent on the temperature, charge rate, and number of charge cycles. Additional charge cycles at these elevated temperature conditions are likely to result in noticeable amounts of degradation.

C.5 Conclusion

The tests described in Section C were performed to evaluate the charging profile of the pack at a temperature higher than the specified cell operating range. Only the Pair 2 OEM – Pack prevented charging at a specific temperature (45 °C) within this testing profile. Given that the allowable maximum temperature during charging for all tested cells ranges from 40 – 45 °C (Section B.4.1), four of the five test packs allowed cells to charge at temperatures exceeding the specifications. Exposure to abusive elevated temperatures can cause the cells to degrade, causing performance loss and an increase in the probability of a safety hazard.

For Pair 2 OEM – Pack, the temperature at which the charging was interrupted (45 °C) was consistent with the cell specification limits.

All but the Pair 2 Rep – Pack was determined to have functionality already set up to prevent charging beyond a specified temperature values (Section B.3.6.2). For three of these four packs, it appears that the temperature set point is beyond what was tested in this protocol, and beyond the cell specification limits.

D. Ambient Temperature Decreasing During Charging

D.1 Introduction

Exponent performed a test on each pack, characterizing a charging scenario where the environmental temperature of the pack starts at ambient conditions and decreases while the pack still charges. As described in Section C – Ambient Temperature Increasing During Charging, it is best practice to restrict the temperature range at which a battery pack can be charged, both at lower and upper temperature limits.

The tests evaluated the battery pack response to a 26 °C decrease in environmental temperature below ambient conditions. The cells in the five battery pack types have a lower temperature limit during charge of either 10 °C or 0 °C per their specification sheet (see Table 12). The testing protocol resulted in exposing the cells in the battery packs to temperatures below that limit while charging.

D.2 Test Overview

The tests were carried out in a temperature-controlled chamber (ESPEC P-300). K-type thermocouples were used to measure all the temperatures. A Graphtec GL-840 was used as the data logger to record the temperatures, voltages, and currents. The testing protocol is as follows:

1. Each pack was instrumented with at least five thermocouples. Three thermocouples were placed internally (Location 1, 2, and 3) and two were placed externally (Location 4 and 5). One thermocouple (Location 1) was placed adjacent to the temperature sensor location for each pack.
2. Each pack was instrumented to record pack voltage and pack current during charging.
3. Each pack was fully discharged (at 0.5 C-rate) prior to charging.
4. Each pack was charged by using the supplied (intended) charger.
5. The tests were performed in a controlled thermal chamber as follows:
    a. Each pack was soaked at 23 ºC for 30 minutes before starting the charging. The charger remained outside the chamber at ambient temperature.

b. The thermal chamber temperature was decreased to -3 ºC (± 3 ºC) at a rate of 10 ºC per hour.
c. The chamber temperature was maintained at -3 ºC during the remainder of test.
d. Charging was stopped when the pack was fully charged (charge current has stopped flowing) or stopped charging at least for 60 minutes.

D.3 Results

Table 17 includes the overview of the test results for all 5 packs. Table 18 lists the temperatures, voltages and currents recorded during the test for all 5 packs.

Table 17. Section D test results overview

Pack	Protocol Completion Summary
Pair 1 OEM	Charging protocol performed to completion
Pair 1 Rep	Charging protocol performed to completion
Pair 2 OEM	Charging protocol performed to completion
Pair 2 Rep	Charging protocol performed to completion
Solo	Charging protocol performed to completion

Table 18. Section D test metrics

Pack	Initial Charging Temp (ºC)	Minimum Internal Temp (ºC)[29]	Minimum External Temp (ºC)[30]	Pack Voltage at 0 ºC (V)	Final Charging Voltage (V)	Temp Specifications for Cells (ºC)	Capacity (Ah)	Rated Capacity (Ah)	Charge Current Cut-off (A)
Pair 1 OEM	22	-2.6	-2.7	51.5	54.6	0 – 45	8.8	12.8	0.7
Pair 1 Rep	21	-2.5	-3.2	51.1	54.6	10 – 45	8.7	14	0.36
Pair 2 OEM	20	-3.4	-3.4	50.0	54.6	0 – 45	9.5	14	0.17
Pair 2 Rep	21	-2.6	-3.6	47.7	54.6	0 – 40	11.6	15	n/a[31]
Solo	23	-3	-3.5	48.6	54.6	10 – 45	8.4	12.8	0.22

[29] These are the minimum internal temperatures that were recorded during the test.

[30] These are the minimum external temperatures that were recorded during the test.

[31] Charging was stopped manually since this pack did not have a current cut-off.

D.4 Discussion

D.4.1 Pair 1 OEM

The Pair 1 OEM – Pack was charged with the specified charger. During the test, as the temperature ramped down to -3 °C, the pack completed a full charging cycle in 3 hours and 27 minutes. The charging stopped at 54.5 V when the current decreased to 0.7 A (see Figure D - 1). The charging current cut-off was higher than what was observed during the charge characterization test at ambient temperature (0.16 A). The charging capacity of the pack was calculated to be approximately 8.8 Ah, which is significantly lower than the rated capacity (12.8 Ah). The lower capacity of the pack can be attributed to the colder environment as it significantly slows down the ion transport mechanism within the cells. During charging, the internal temperature of the pack was recorded at -2.6 ºC, which represents the minimum cell surface temperature. This temperature was lower than the recommended minimum charging temperature as mentioned in the cell specification sheet (0 – 45 ºC).

D.4.2 Pair 1 Rep

The Pair 1 Rep – Pack was charged with the specified charger. During the test, as the temperature ramped down to -3 °C, the pack completed a full charging cycle in 3 hours and 48 minutes. The charging stopped at 54.6 V when the current decreased to 0.36 A (see Figure D - 2). The pack voltage and charging current cut-off were similar to what was observed during the charge characterization test at ambient temperature. The charging capacity of the pack was calculated to be approximately 8.7 Ah, which is significantly lower than the rated capacity (14 Ah). The lower capacity of the pack can be attributed to the colder environment as it significantly slows down the ion transport mechanism within the cells. During charging, the internal temperature of the pack was recorded at -2.5 ºC, which represents the minimum cell surface temperature. This temperature was lower than the recommended minimum charging temperature as mentioned in the cell specification sheet (0 – 45 ºC).

D.4.3 Pair 2 OEM

The Pair 2 OEM – Pack was charged with the specified charger. During the test, as the temperature ramped down to -3 °C, the pack completed a full charging cycle in 4 hours and 24 minutes. The charging stopped at 54.6 V when the current decreased to 0.17 A (see Figure D - 3). The pack voltage and charging current cut-off were similar to what was observed during the charge characterization test at ambient temperature. The charging capacity of the pack was calculated to be approximately 9.5 Ah, which is significantly lower than the rated capacity (14 Ah). The lower capacity of the pack can be attributed to the colder environment as it significantly slows down the ion transport mechanism within the cells. During charging, the internal temperature of the pack was recorded at -3.4 ºC, which represents the minimum cell surface temperature. This temperature was lower than the recommended minimum charging temperature as mentioned in the cell specification sheet (0 – 45 ºC).

D.4.4 Pair 2 Rep

The Pair 2 Rep – Pack was charged with the specified charger. During the test, as the temperature ramped down to -3 °C, the pack completed a full charging cycle in 10 hours and 23 minutes. No cut-off for charging current was observed during the test as the current kept gradually decreasing until it was manually stopped. The final pack voltage was 54.5 V at approximately 0.03 A (see Figure D - 4). A similar charge profile was observed during the charge characterization test at ambient temperature. The lack of a charging cut-off may allow the pack to be overcharged if connected to the charger for an extended period of time (i.e., float charged). When overcharged, Li-ion batteries may experience overheating, which can result in a thermal event. The cells can also experience degradation resulting in reduced discharge capacities, which leads to shorter cell lifetimes. The charging capacity of the pack was calculated to be approximately 11.6 Ah, which is significantly lower than the rated capacity (14 Ah). The lower capacity of the pack can be attributed to the colder environment as it significantly slows down the ion transport mechanism within the cells. During charging, the internal temperature of the pack was recorded at -2.6 ºC, which represents the minimum cell surface temperature. This temperature was lower than the recommended minimum charging temperature as mentioned in the cell specification sheet (0 – 45 ºC).

D.4.5 Solo

The Solo – Pack was charged with the specified charger. During the test, as the temperature ramped down to -3 °C, the pack completed a full charging cycle in 5 hours and 31 minutes. The charging stopped at 54.6 V when the current decreased to 0.22 A (see Figure D - 5). The pack voltage and charging current cut-off were similar to what was observed during the charge characterization test at ambient temperature. The charging capacity of the pack was calculated to be approximately 8.4 Ah, which is significantly lower than the rated capacity (12.8 Ah). The lower capacity of the pack can be attributed to the colder environment as it significantly slows down the ion transport mechanism within the cells. During charging, the internal temperature of the pack was recorded at -3 ºC, which represents the minimum cell surface temperature. This temperature was lower than the recommended minimum charging temperature as mentioned in the cell specification sheet (0 – 45 ºC).

D.4.6 Cell Evaluation

Three cells from each tested pack were evaluated for signs of degradation via CT scanning. No obvious signs of material deposits, gas formation or other forms of degradation were observed. Even though all five packs were able to perform a charge below the cell specification sheet minimum temperature, damage to these cells is expected to be limited. Damage to cells charged at low temperatures typically presents in the form of lithium plating. The extent of lithium plating is dependent on the temperature, charge rate, and number of charge cycles. While these cells are not expected to have appreciable amounts of lithium plating or other degradation after a single charge at low temperature, continued use at these conditions may result in noticeable amounts of degradation.

D.5 Conclusion

The tests were performed to evaluate the charging profile of the pack at temperature (-3 °C) lower than the specified cell operating range. All the five packs allowed charging at the lowest temperature during the tests. Per cell specifications, the minimum allowable charging temperatures for the cells in these packs ranged between 0 and 10 °C (Section B.4.1). The testing protocol in this section brought the interior of the packs to a minimum temperature of -2.5 °C to -3.6 °C and still allowed charging to continue.

From testing in Section B.3.6.2, three of the five pack types, including the two OEM packs, appeared to have functionality to prevent charging below a specified temperature. However, the observations were based on pack external temperatures which did not represent the internal cell temperatures. The exact low temperature cut-off thresholds were not determined.

Exposure to abusive low temperatures can cause the cells to degrade faster and form lithium plating on negative electrodes. This can cause significant capacity loss and pose various safety concerns like lithium dendrite-induced shorting.[32]

From the cell level testing, single exposure through this protocol to completion does not appear to create an excessive or obvious amount of damage that would be visualized in CT data. However, continued or more extreme usage similar to this protocol may lead to capacity loss and potential safety risks. This has not been tested during this evaluation.

[32] Luo, H. et.al., " Lithium-Ion Batteries under Low-Temperature Environment: Challenges and Prospects", Materials, 15 (22): 8166, 2022. doi: 10.3390/ma15228166.

E. Out-of-Specification Charger Current Test

E.1 Introduction

Exponent performed a test on each pack, characterizing a charging scenario where an unintended charger was used that supplied a current higher than the rated output of the intended charger.

It is best practice to restrict the charging current to a value within the specified allowable range. The rated output of the intended charger is assumed to be within that range. As Exponent was not provided a specifications sheet for any of the battery packs, it is unknown if the charging current of the intended charger is at or below the maximum allowable current. Often devices containing lithium-ion batteries are charged at a rate lower than the maximum allowable current, to prolong product lifetime (i.e., decrease the rate of degradation), or for logistical or financial reasons, etc. The value of maximum allowable charge current in a pack is usually determined through several factors, including the individual cell ratings, protection hardware, and testing.

As found in Pack-level Testing (see Table 10), all five packs have short-circuit protections to prevent an over-current situation. Exponent did not test if there was a specific charging current cut-off mechanism in the packs.

Charging at a higher-than-intended current can result in an elevated safety risk through damage to the cells, or to the current carrying cables and traces if they are not appropriately rated. Cells that are charged at a higher-than-intended current can result in the formation of plated lithium metal, formation of solid and gaseous electrolyte degradation products, metal dissolution from the positive electrode or some combination thereof. The extent of cell degradation generally scales with the amount of current above the maximum rating and the cumulative amount of time at this charging current (i.e., number of charges).

E.2 Test Overview

The tests were carried out using a DC power supply (BK Precision 9116). K-type thermocouples were used to measure all the temperatures. A Graphtec GL-840 was used as the data logger to record the temperatures, voltages, and currents. The testing protocol is described as follows:

1. Each pack was instrumented with two thermocouples for the pack (one interior, one exterior) and one thermocouple to record the ambient temperature.
2. Each pack was instrumented to record the pack voltage and charge current, and power supply voltage and current.
3. The tests were performed at room temperature using the following protocol:
    a. Each pack was fully discharged (at 0.5 C-rate) prior to charging.
    b. The output voltage for the DC power supply used in place of the intended charger during this testing was set to 56 V.
    c. Each pack was charged using the DC power supply with the current limit set to twice the rated output current of the supplied charger. For example, the current limit set for the Pair 1 OEM – Pack was 6 A (twice the rated current, 3 A).
    d. The tests were terminated when the charge current stopped flowing for at least 5 minutes.

Since the designated charger was not used for these tests, the power supply was conservatively set to a voltage limit exceeding the rated output voltage of the charger, in order to ensure the testing characterized the entire intended charging voltage curve.

E.3 Results

Table 19. Section E Test Results Overview

Pack	Protocol Completion Summary
Pair 1 OEM	Charging protocol performed to completion
Pair 1 Rep	Charging protocol performed to completion
Pair 2 OEM	Charging protocol performed to completion
Pair 2 Rep	Charging protocol performed to completion
Solo	Charging protocol performed to completion

Table 20. Section E Test Metrics

Pack	Charging Current (A)	Pack Charging Voltage Cut-off (V)	Stack Charging Voltage Cut-off (V)	Cell Group Charging Voltage Cut-off (V)[33]	Maximum Internal Temperature (ºC)	Charging Voltage Rebound	Cell Group Voltage Imbalance
Pair 1 OEM	6	56.0	55.3	4.25	34.7	Yes	No
Pair 1 Rep	6	55.3	54.8	4.24	35.4	Yes	No
Pair 2 OEM	6	56.3	55.2	4.24	36.2	No	No
Pair 2 Rep	4	55.6	54.6	4.20	32.2	No	Yes
Solo	4	56.1	55.2	4.25	31.4	Yes	Yes

[33] Cell group charging voltage cut-off was calculated by dividing the stack voltage with number of series cell groups within a pack.

E.4 Discussion

E.4.1 Pair 1 OEM

The Pair 1 OEM – Pack was charged using the DC power supply with the current limit set to 6 A. During the period of charging at twice the rated current, the pack completed the charging cycle in approximately 2 hours before the overvoltage protection was activated and the charge current stopped. The final pack and corresponding stack voltages were 56 V and 55.3 V respectively (see Figure E - 1). The final stack voltage (55.3 V) corresponds to 4.25 V per cell group. Per the cell specifications, the maximum charge voltage for the individual cells is 4.2 ± 0.05 V. After the charging current stopped, and as the pack voltage started dropping, charge current started flowing again (at least three times within the first 5 minutes) when the cell stack relaxed to 53.91 V (approximately 4.15 V per cell group). This continued until the pack voltage reached 56 V each time. No elevated internal temperatures were observed during the test. No post-test voltage imbalance was observed in this pack.

E.4.2 Pair 1 Rep

The Pair 1 Rep – Pack was charged using the DC power supply with the current limit set to 6 A. During the period of charging at twice the rated current, the pack completed the charging cycle in approximately 1 hour and 55 minutes before the overvoltage protection was activated and the charge current stopped. The final pack and the corresponding stack voltages were 55.8 V and 55.1 V respectively (see Figure E - 2). The final stack voltage (55.1 V) corresponds to 4.24 V per cell group. After the charging current stopped, and as the pack voltage started dropping, charge current started flowing again (once within the first 10 minutes) when the cell stack relaxed to 53.3 V (approximately 4.1 V per cell group). No elevated internal temperatures were observed during the test. No post-test voltage imbalance was observed in this pack.

E.4.3 Pair 2 OEM

The Pair 2 OEM – Pack was charged using the DC power supply current limited to 6 A. During the period of charging at twice the rated current, the pack completed the charging cycle in approximately 2 hours and 10 minutes before the overvoltage protection was activated. The pack and the corresponding stack voltages at the end of charging were 56.3 V and 55.1 V which corresponds to 4.24 V per cell group (see Figure E - 3). Per the cell specifications, the maximum charge voltage for the individual cells is limited to 4.2 ± 0.05 V. No elevated internal temperatures were observed during the test. No post-test voltage imbalance was observed in this pack.

E.4.4 Pair 2 Rep

The Pair 2 Rep – Pack was charged using the DC power supply current limited to 4 A. During the period of charging at twice the rated current, the pack completed the charging cycle in approximately 3 hours and 25 minutes before the overvoltage protection was activated and the charge current stopped flowing. The pack and the corresponding stack voltages at the end of charging were 55.6 V and 54.6 V respectively (see Figure E - 4). The final stack voltage (54.6 V) corresponds to 4.2 V per cell group. Per the cell specification sheet, the maximum charge voltage for the individual cells is limited to 4.2 ± 0.05 V. No elevated internal temperatures were observed during the test. When the pack was disassembled post-test, a voltage imbalance in five of the cell groups ranging from 80-210 mV was observed. This imbalance can further be exacerbated if no cell balancing is performed within the pack and potentially affect its capacity and performance.

E.4.5 Solo

The Solo – Pack was charged using the DC power supply with the current limit set to 4 A. During the period of charging at twice the rated current, the pack completed the charging cycle in approximately 2 hours and 53 minutes before the overvoltage protection was activated and the charge current stopped flowing. The pack and the corresponding stack voltages at the end of charging were 56.1 V and 55.2 V (see Figure E - 5). The final stack voltage (55.2 V) corresponds to approximately 4.25 V per cell group. Per the cell specification, the maximum charge voltage for the individual cells is limited to 4.15 -4.2 V. Overcharging the cells can lead to electrolyte degradation and an increase in cell impedance. After the charging current stopped, and as the pack voltage started dropping, charge current started flowing again (once within the first 10 minutes) when the cell stack relaxed to 53.8 V (approximately 4.14 V per cell group). No elevated internal temperatures were observed during the test. When the pack was disassembled post-test, a voltage imbalance in five of the cell groups ranging from 40-50 mV was observed. This imbalance can further be exacerbated if no cell balancing is performed within the pack and potentially affect its capacity and performance.

E.4.6 Cell Evaluation

Three cells from each tested pack were evaluated for signs of degradation via CT scanning. No obvious signs of material deposits, gas formation or other forms of degradation were observed. Exponent did not receive specifications for any of the battery packs. As a result, it is unclear if charging the pack at a current higher than the rating of specified charger would create an "out-of-specification" charging profile. As mentioned earlier, chargers are not necessarily designed with an output current that matches the maximum allowable current of the pack. Per cell specifications, the charging currents for all packs did not exceed the maximum current limits for the cells (see Table 21). Exponent did not verify the charging current experienced by each parallel block in the packs and assumed an equal current distribution across the pack. So, while all packs in this section accepted a higher charging current, the cells did not appear to experience any internal damage.

Table 21. Section E Cell Equivalent Charging Currents

Pack	Pack Charging Current (A)	Cell Equivalent Charging Current (A)	Maximum Charging Current from Cell Specification Sheet (A)
Pair 1 OEM	3	0.750	3.100
Pair 1 Rep	3	0.750	1.675
Pair 2 OEM	3	0.750	3.400
Pair 2 Rep	2	0.667	1.300
Solo	2	0.500	0.910

E.5 Conclusion

The tests described in Section E were performed to evaluate the pack protection against higher than the intended charger input currents. When connected to an external power source providing twice the rated currents, all five packs allowed the cells to be charged until the overcharging protection activated. The interior temperatures of all the five packs remained below 40 ºC during the tests. Post-test disassembly showed noticeable voltage imbalances between cell groups for Pair 2 Rep – Pack and Solo – Pack. It should be noted that the voltage curve of a lithium-ion cell versus SOC is steepest at low SOCs; voltage differences due to any imbalance present will be largest at low SOCs. A determination of SOC differences between the cell groups requires more analysis which was outside of the scope of this project.

Although the cause for voltage imbalance could not be correlated to the excess charge current, continued use of the packs with an unintended charger that provides an excess charge current may cause further imbalance and potential for overcharging individual cells.

From the cell level testing, single exposure through this protocol to charge completion did not appear to create an observable amount of damage that could be visualized in CT data.

F. Out-of-Specification Charger Voltage Test

F.1 Introduction

Exponent performed a test on each pack, characterizing a charging scenario where an unintended charger was used that supplied a voltage higher than the rated output of the intended charger. It is best practice to restrict the input charging voltage to a pack (i.e., output voltage from the charger power supply) to a value at or below the specifications' allowable upper voltage.

Critically, in the case where the input pack charging voltage is greater than intended, the battery pack should ideally have functionality to protect the cells from experiencing the overvoltage condition (i.e., overcharge condition). The primary safety risk of an overcharged battery pack is the stability of the cells.

Overcharging lithium-ion cells can result in lithium plating, gas generation, SEI layer breakdown and, in extreme circumstances, decreased thermal stability and thermal runaway. As is the case with too much charging current (described in the E-bike Charging Overview), the risk generally increases with increasing voltage and the amount of time experienced at that voltage.

Best practice is to design a battery system such that the voltage value that triggers the overvoltage protection is slightly above the intended upper voltage, to minimize any overcharging of the cells and to minimize instances of undercharging the cell by triggering overvoltage protection prematurely. Importantly, the overvoltage protection circuitry is considered part of the backup safety protection circuitry and should not be relied upon as a core function of the pack as this would theoretically allow for repeated overcharging of a battery with continued usage. In a battery pack, there is often the ability to sense the voltages of each parallel string of cells to prevent any individual cell from being overcharged rather than the pack.

As will be shown in the results of this testing section, charging an e-bike pack with a higher-than-intended output voltage from the charger can result in the pack terminating the charge using the overvoltage protection circuitry. In these situations, if the cells experience voltages higher than the specifications' allowable upper voltage, they should be considered overcharged.

F.2 Test Overview

F.2.1 Pack Testing

The tests were carried out by using a DC power supply (BK Precision 9116). K-type thermocouples were used to measure all the temperatures. Graphtec GL-840 was used as the data logger to record the temperatures, voltages and currents. The testing protocol was as follows:

1. Each pack was instrumented with two thermocouples for the pack (one interior, one exterior) and one thermocouple to record the ambient temperature.
2. Each pack was instrumented to record the voltage and current from the pack, cell stack, and power supply.
3. The tests were performed at room temperature and the test protocol was as follows:
    a. Each pack was fully discharged (at 0.5 C-rate) prior to charging.
    b. The output voltage for the DC power supply was set at 125% of the rated charger output voltage. For example, the output voltage for the Pair 1 OEM – Pack was 68.2 V (25% over the rated voltage, 54.6 V).
    c. The charging current from the DC power supply was set to the charger specified current for each pack. For example, the charging current for the Pair 1 OEM – Pack was 3 A.
    d. Charging was terminated when the charge current stopped flowing for at least 5 minutes.

F.2.2 Cell Testing

During pack-level overvoltage testing it was learned that all the packs consistently allowed slight overcharging of the cells. Based on these results, Exponent decided to perform a short cell-level cycling test to simulate cells being repeatedly charged under the conditions recorded during the pack level tests. Two cells extracted from unused packs were used for these tests.

Cell tests were carried out using a Maccor battery cycler (Series 4000M). The cycling protocol was as follows:

1. Cells were connected to the battery cycler and instrumented with K-type thermocouples placed on the middle of each cell surface.
2. Each cell was discharged at a 0.5 C-rate to 3.0 V.
3. Cells were cycled for two weeks. This cycling protocol is summarized in Table 22.
4. One cycle consists of:
    a. Charge at a constant current to 4.25 V.
        i. The charge current used is pack type specific (Table 22) based on the charger ratings (Table 3).
    b. Rest for 4 hours
        i. If the OCV of the cells fell below a predetermined threshold voltage (top off charge voltage [TOCV] in Table 22), the cell was allowed to charge again to 4.25 V at the charge current used in the previous step. This constituted one top-off cycle.
            1. Three packs that were not observed in pack testing to have any top-off charging were set to TOCV values of 3.5 V, which resulted in no top-off charges.
    c. Discharge at a 0.5 C-rate until a cut-off voltage of 3.0 V is reached.
    d. Rest for 10 minutes.
5. After the charging period was concluded, cells were then charged to 100% SOC using the cell specification sheet standard charge. After the top-off charge protocol was completed, cells were disassembled in an argon-filled glovebox for analysis.

Table 22. Pack specific cell cycling parameters for F.2.2.

Pack	Charging Current [mA]	Voltage Cut-offs	Top-off Charge Voltage [V]	Discharge Current [mA]
Pair 1 OEM	750	Charge: 4.25 V Discharge: 3.0 V	4.15 V	1600
Pair 1 Rep	750	Charge: 4.25 V Discharge: 3.0 V	3.5 V	1650

Pack	Charging Current [mA]	Voltage Cut-offs	Top-off Charge Voltage [V]	Discharge Current [mA]
Pair 2 OEM	750	Charge: 4.25 V Discharge: 3.0 V	3.5 V	1750
Pair 2 Rep	330	Charge: 4.25 V Discharge: 3.0 V	3.5 V	866.6
Solo	500	Charge: 4.25 V Discharge: 3.0 V	4.14 V	1490

F.3 Results

Table 23. Section F Test Results Overview

Pack	Protocol Completion Summary
Pair 1 OEM	Charging protocol performed to completion
Pair 1 Rep	Charging protocol performed to completion
Pair 2 OEM	Charging protocol performed to completion
Pair 2 Rep	Charging protocol performed to completion
Solo	Charging protocol performed to completion

Table 24. Section F Testing Metrics

Pack	Output Voltage from Power Supply (V)	Pack Charging Voltage Cut-off (V)	Stack Charging Voltage Cut-off (V)	Cell Group Charging Voltage Cut-off[34] (V)	Maximum Internal Temp (°C)	Charging Voltage Rebound	Cell Group Voltage Imbalance
Pair 1 OEM	68.2	55.5	55.2	4.25	29.2	No	Yes
Pair 1 Rep	68.2	55.5	55.2	4.25	31	No	No
Pair 2 OEM	68.2	56.1	55.2	4.25	32.3	No	No
Pair 2 Rep	68.2	55.8	55.2	4.25	28	No	Yes
Solo	68.2	55.8	55.1	4.24	27.8	No	No

34 Cell group charging voltage cut-off was calculated by dividing the stack voltage with number of series cell groups within a pack.

F.4 Discussion

F.4.1 Pair 1 OEM

The Pair 1 OEM – Pack was charged using the DC power with the current limit set to 3 A. During the test period, the pack completed the charging cycle in 4 hours and 9 minutes before the overvoltage protection was activated and the charge current stopped. The final pack and corresponding stack voltages were 55.5 V and 55.2 V respectively (see Figure F - 1). The final stack voltage (55.2 V) corresponds to 4.25 V per cell group. Per the cell specifications, the maximum charge voltage for the individual cells is limited to 4.2 ± 0.05 V. No elevated internal temperatures were observed during the test. When the pack was disassembled post-test, a voltage imbalance in four of the cell groups ranging from 70 – 100 mV was observed. This imbalance can further be exacerbated if no cell balancing is performed within the pack and potentially affect its capacity and performance.

F.4.2 Pair 1 Rep

The Pair 1 Rep – Pack was charged using the DC power supply with the current limit set to 3 A. During the test period, the pack completed the charging cycle in 4 hours and 8 minutes before the overvoltage protection was activated and the charge current stopped. The final pack and corresponding stack voltages were 55.5 V and 55.2 V respectively (see Figure F - 2). The final stack voltage (55.2 V) corresponds to 4.25 V per cell group. Per the cell specification sheet, the maximum charge voltage for the individual cells is limited to 4.2 ± 0.03 V. Overcharging of cells can lead to electrolyte degradation and an increase in cell impedance. Overcharging can also introduce voltage imbalance among cell groups due to changes in cell impedances. However, when the pack was disassembled post-test, no voltage imbalance was observed in this pack. No elevated internal temperatures were observed during the test.

F.4.3 Pair 2 OEM

The Pair 2 OEM – Pack was charged using the DC power supply with the current limit set to 3 A. During the test period, the pack completed the charging cycle in 4 hours and 23 minutes before the overvoltage protection was activated and the charge current stopped. The final pack and corresponding stack voltages were 56.1 V and 55.2 V respectively (see Figure F - 3). The final stack voltage (55.2 V) corresponds to 4.25 V per cell group. Per the cell specification sheet, the maximum charge voltage for the individual cells is limited to 4.2 ± 0.05 V. No elevated internal temperatures were observed during the test. No post-test voltage imbalance was observed in this pack.

F.4.4 Pair 2 Rep

The Pair 2 Rep – Pack was charged using the DC power supply with the current limit set to 2 A. During the test period, the pack completed the charging cycle in 7 hours and 51 minutes before the overvoltage protection was activated and the charge current stopped. The final pack and corresponding stack voltages were 55.8 V and 55.2 V (see Figure F - 4). The final stack voltage (55.2 V) corresponds to 4.25 V per cell group. Per the cell specifications, the maximum charge voltage for the individual cells is limited to 4.2 ± 0.05 V. No elevated internal temperatures were observed during the test. When the pack was disassembled post-test, a voltage imbalance in four of the cell groups ranging from 180 – 200 mV was observed. This imbalance can further be exacerbated if no cell balancing is performed within the pack and potentially affect its capacity and performance.

F.4.5 Solo

The Solo – Pack was charged using the DC power supply with a current limit set to 2 A. During the test period, the pack completed the charging cycle in 5 hours and 57 minutes before the overvoltage protection was activated and the charge current stopped. The final pack and corresponding stack voltages were 55.8 V and 55.1 V (see Figure F - 5). The final stack voltage (55.1 V) corresponds to 4.24 V per cell group. Per the cell specifications, the maximum charge voltage for the individual cells is limited to 4.15-4.20 V. Overcharging of cells can still lead to electrolyte degradation and an increase in cell impedance. Overcharging can also introduce voltage imbalance among cell groups due to changes in cell impedances. However, when the pack was disassembled post-test, no voltage imbalance was observed in this pack. No elevated internal temperatures were observed during the test.

F.4.6 Cell-level Charging with Top-off Charge Criteria

Based on observations that pack charging was terminated using the overvoltage protection circuitry, which is set at a slightly higher voltage than during nominal charging, Exponent performed cycling tests on cells to understand the relative safety implications of the pack test results. In each of the five cell types tested, charging was cut off at a voltage slightly higher than the intended charger cut-off, approximately 50 mV per cell.

Cells from each pack were constant current charged to 4.25 V. Two of the cell types tested included an additional portion of the charging protocol that allowed for a top off charge if the cell voltage relaxed within a 4-hour period. This addition was included based on observations of top off from pack level testing in this section and to try to emulate a pack connected to a charger for an extended period time after completing its charge (i.e., overnight). The cycling results are summarized in Figure 26.

The capacity retention of the cells was qualitatively similar to those tested against the cell specifications sheet protocol in Section B.4.1, given the differences in protocols.

Based on the results of this testing, the cells neither lost excess charge capacity, nor showed obvious signs of degradation that would create an elevated safety risk compared to cells cycled under nominal conditions. However, this result is only valid for the number of cycles used in this test. Repeated cycling under this scenario may lead to cell degradation and potential safety risks, but the required long-term testing was outside of the scope of this project.

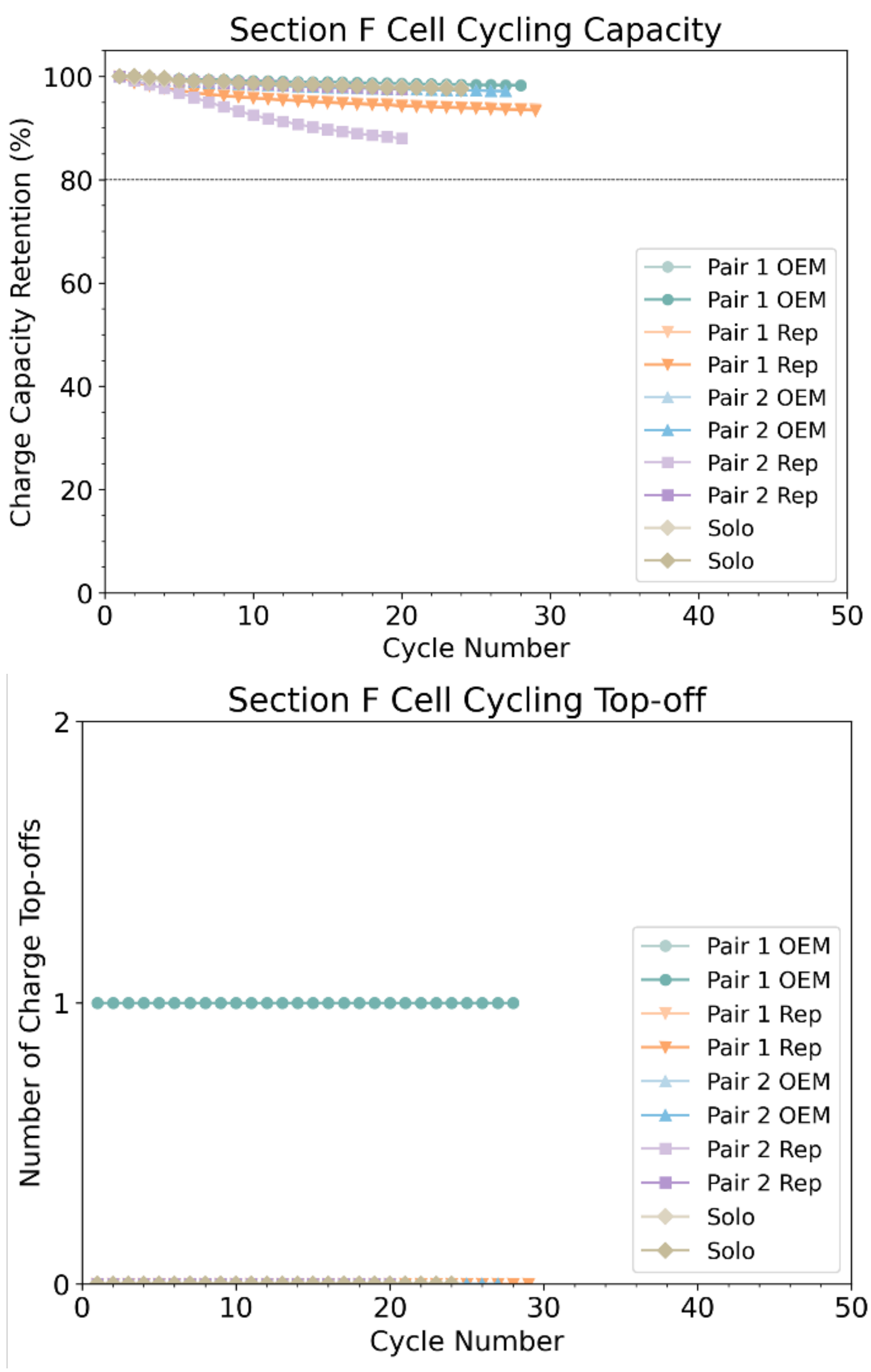


Figure 23. Section F.2.2 cell cycling capacity retention (top) and number of top-offs per cycle (bottom).

Observations from the teardown of the cycled cells were similar to those of the cycled cells tested in Section B.4.4. In Figure 27, lithium plating was observed in the Solo cells. In Figure 28, some signs of under-lithiation of the charged negative electrode were observed. The presence of a charge top-off per cycle in the Pair 1 OEM cycled cells did not result in an appreciable change in cycling performance or increase in capacity degradation. These observations and those in Appendix F are similar to those from the nominally cycled cells.

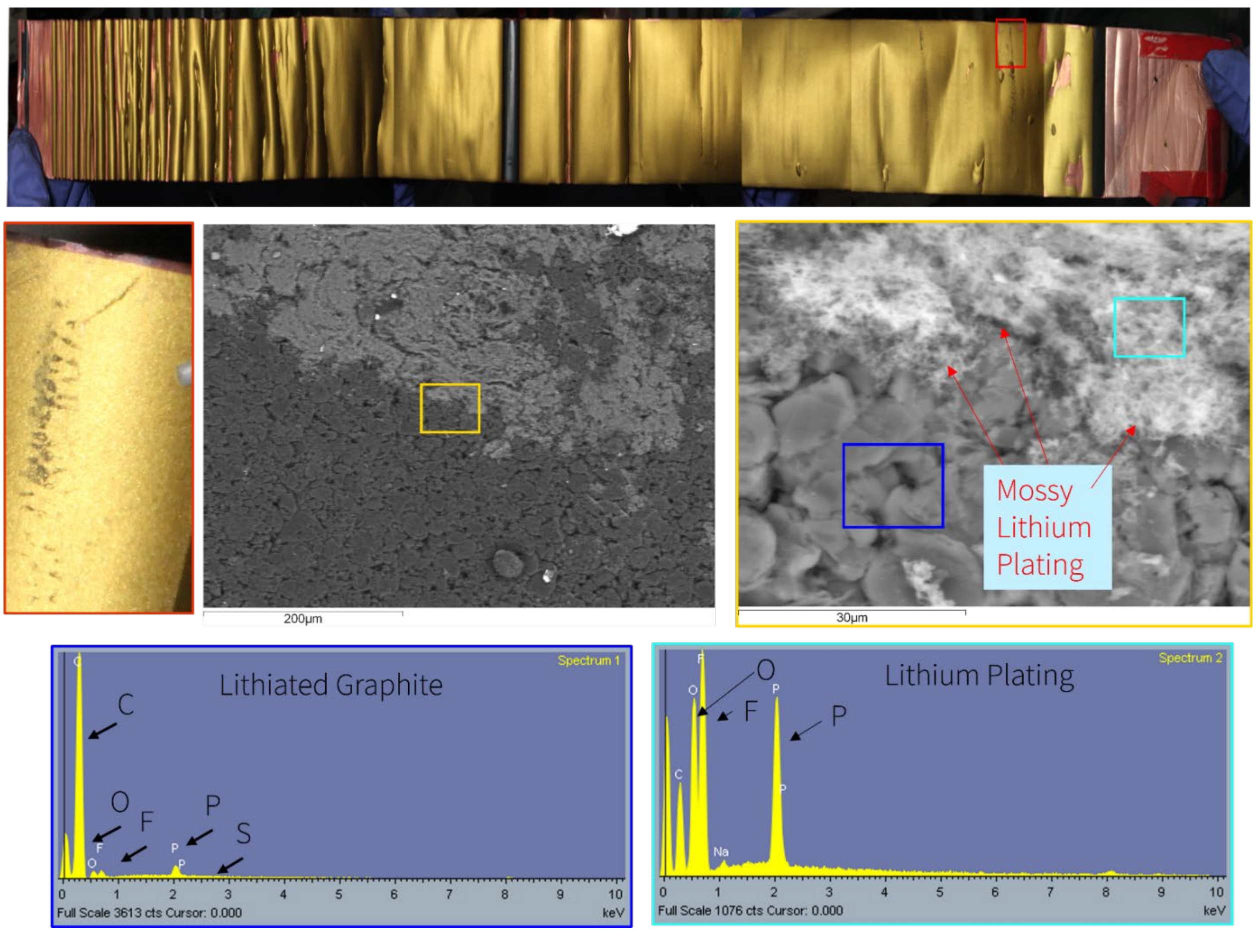


Figure 24. Solo – Pack disassembled inner winding showing signs of lithium plating.

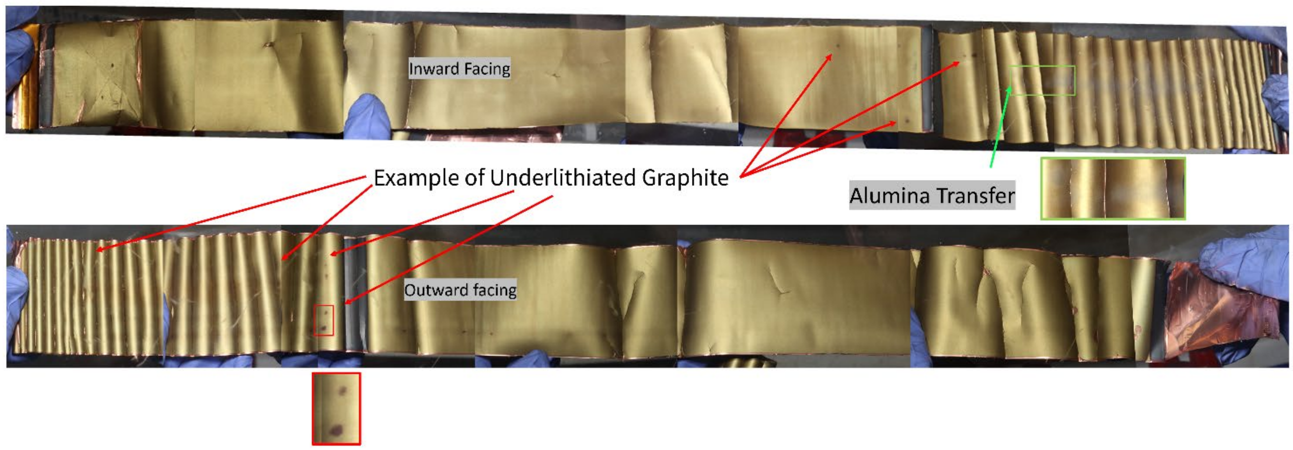


Figure 25. Pair 2 Rep – Pack negative windings at 100% SOC exhibiting signs of under-lithiation.

F.5 Conclusion

All packs tested in this protocol were able to be charged with an unintended charger that supplied a voltage higher than the rated output of the intended charger. The packs experienced voltages slightly above their intended upper voltage limit (i.e., the output voltage of the intended charger). It appears that all the packs rely upon the overvoltage protection circuitry to terminate the charge. This indicates that there is no functionality in the packs to restrict or modulate the input voltage to the intended charger voltage.

While the packs experienced voltages slightly above the intended voltage from the supplied charger, three aspects of the charging profiles in these tests appear to restrict the cells from overcharge, and thus, the potential hazard. First, the voltage setpoint for the overvoltage protection was close to the nominal charge upper voltage (within approximately 50 mV). Second, per cell specifications, four out of the five cells allowed for a 30 mV – 50 mV tolerance in the upper voltage limit (i.e., up to 4.23 V – 4.25 V). Third, the charging protocols terminated in a constant current (CC) mode rather than the typical constant voltage (CV) mode. The combined impacts of these three features resulted in the cells experiencing minimal time above the intended pack upper voltage limit, as the cells quickly relax in voltage (i.e., rebound) below that value.

Exponent performed repeated charge-discharge cycling of cells extracted from each of the packs using a protocol intended to mimic the observed pack charging behavior in this task. Teardown analysis of the cells after cycling did not reveal any obvious signs of degradation in the form of electrolyte degradation or lithium plating. Given the limited number of cycles performed on the cells (30 cycles), it is unclear if this charging condition would result in accelerated degradation of the cells or at what point. At a minimum, it appears that this charging profile does not result in an instantaneous or rapid increase in probability of potential hazard.

Limitations

At the request of the Consumer Product Safety Commission (CPSC), Exponent has conducted an analysis of commercially available lithium-ion battery packs intended for use in electrified bicycles (e-bikes). The goal of this document is to provide an objective assessment of the quality, safety, and fitness-for-use of several examples of readily available e-bike battery packs. No portion of this document constitutes an endorsement or condemnation by Exponent of any of the assessed products.

In this analysis, we have relied upon information provided by various manufacturers' and sellers' websites, as well as information provided by the CPSC. We cannot verify the correctness of this input and rely on the suppliers' information for accuracy.

Although Exponent has exercised usual and customary care in the conduct of this analysis, the responsibility for the findings and interpretation of the findings remains fully with the CPSC.

While the opinions offered in this document illuminate some strengths and weaknesses of the assessed packs and provide some insight into the more general risks associated with e-bike battery pack use, they should not be considered a comprehensive assessment of the included products. Further, the small sample size relative to all the commercially available e-bike battery packs prevents this document from being representative of the entirety of commercially available e-bike battery pack products.

The opinions formulated during this assessment are based on observations, measurements, and information available at the time this document was created. Reasonable and customary care was taken while executing the scientific and engineering testing described in this document. As a result, the opinions presented herein are made to a reasonable degree of scientific and engineering certainty. Exponent has made every effort to accurately and completely consider relevant information pertinent to the topics addressed herein.

This document was created to address topics of specific interest to the CPSC and may not adequately address the needs of other readers of the document. Use of or failure to use information presented herein is at the sole risk of the reader.

Appendix A

Sample Overview

Table A - 1 Battery pack specifications

	Pair 1 OEM	Pair 1 Rep	Pair 2 OEM	Pair 2 Rep	Solo
Capacity (Ah)	12.8	14	14	15	12.8
Nominal Pack Voltage (V)	48	48	48	48	48
Cell Configuration	13s4p	13s4p	13s4p	13s6p	13s4p

Pair 1 OEM – Pack

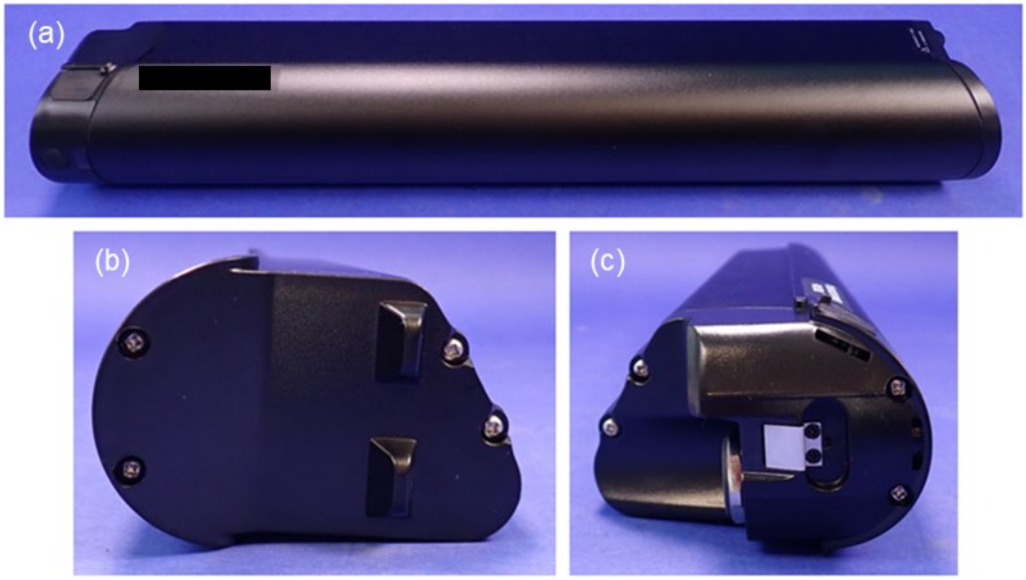


Figure A - 1. Pair 1 OEM – Pack as received; (a) side view; (b) end view; (c) connector-end view of pack housing.

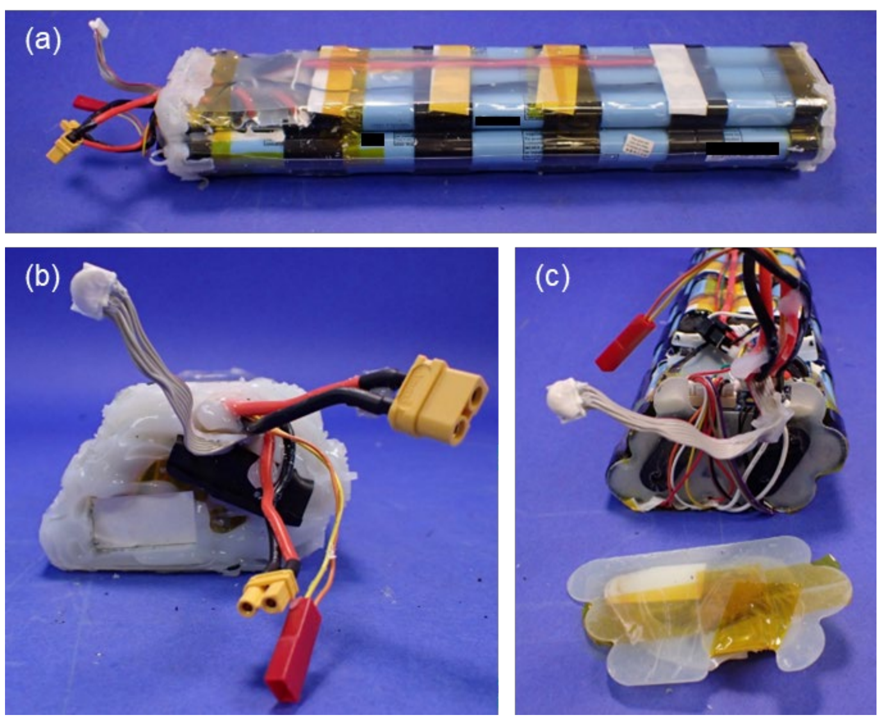


Figure A - 2. Pair 1 OEM – Pack with outer casing removed; (a) cell stack; (b) and (c) cables and connectors for charge and discharging.

Pair 1 Rep – Pack

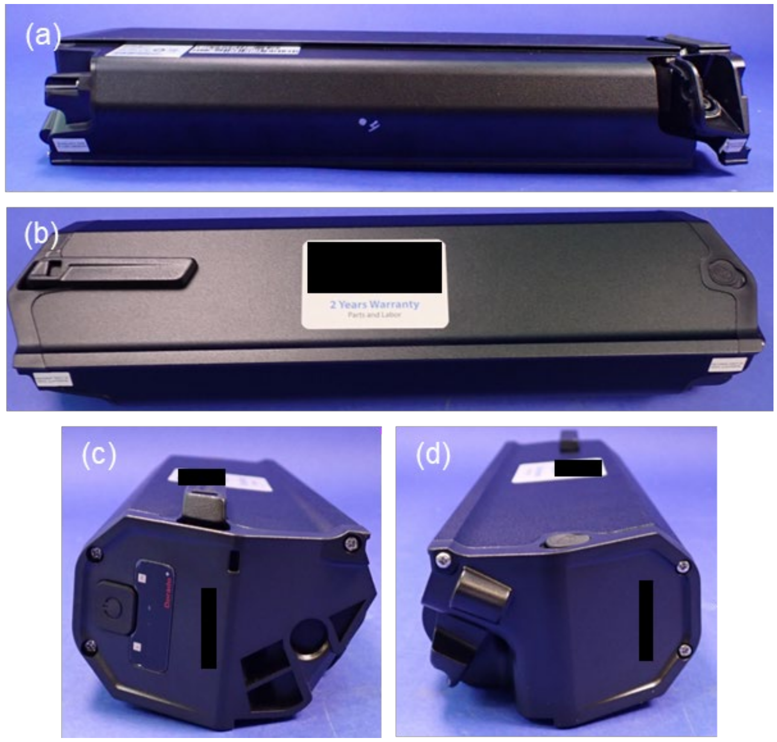


Figure A - 3. Pair 1 Rep – Pack as received; (a) and (b) side views of enclosure; (c) and (d) both ends of the battery pack housing.

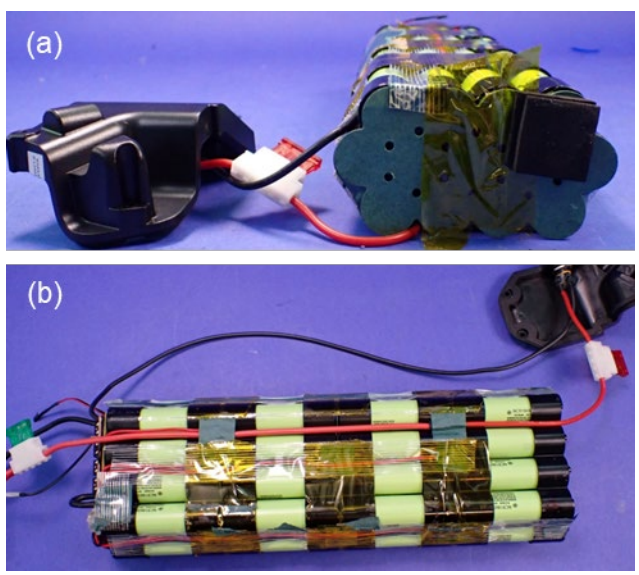


Figure A - 4. Pair 1 Rep – Pack with outer casing removed; (a) end cap view from charge/discharge end, and (b) top/side view of cell stack and cables.

Pair 2 OEM – Pack

Figure A - 5 Pair 2 OEM – Pack as received; (a) and (b) outer enclosure; (c) adapter between stack and load; (d) and (e) end caps with indicators.

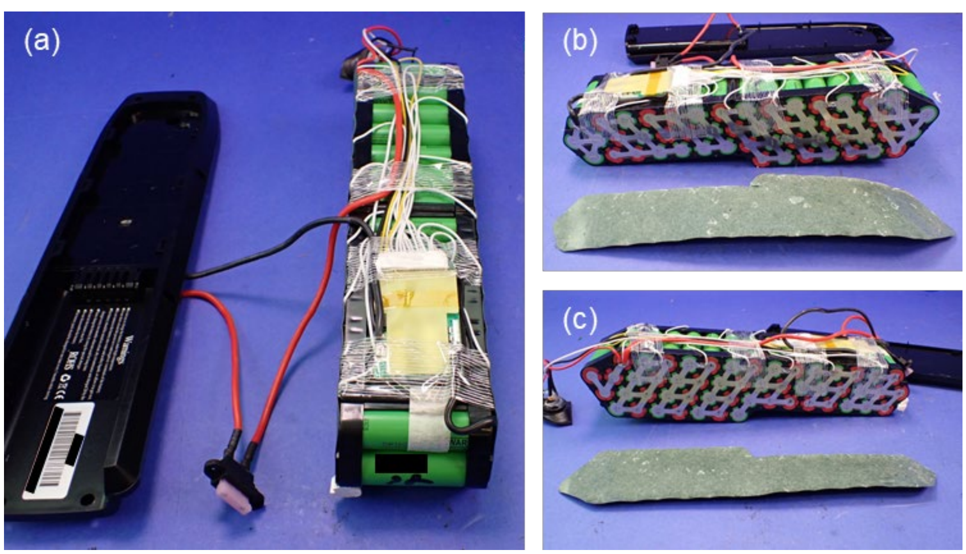


Figure A - 6. Pair 2 OEM – Pack with outer casing removed; (a) top view and (b) and (c) side views of cell stack, fuse, and wire routing.

Pair 2 Rep – Pack

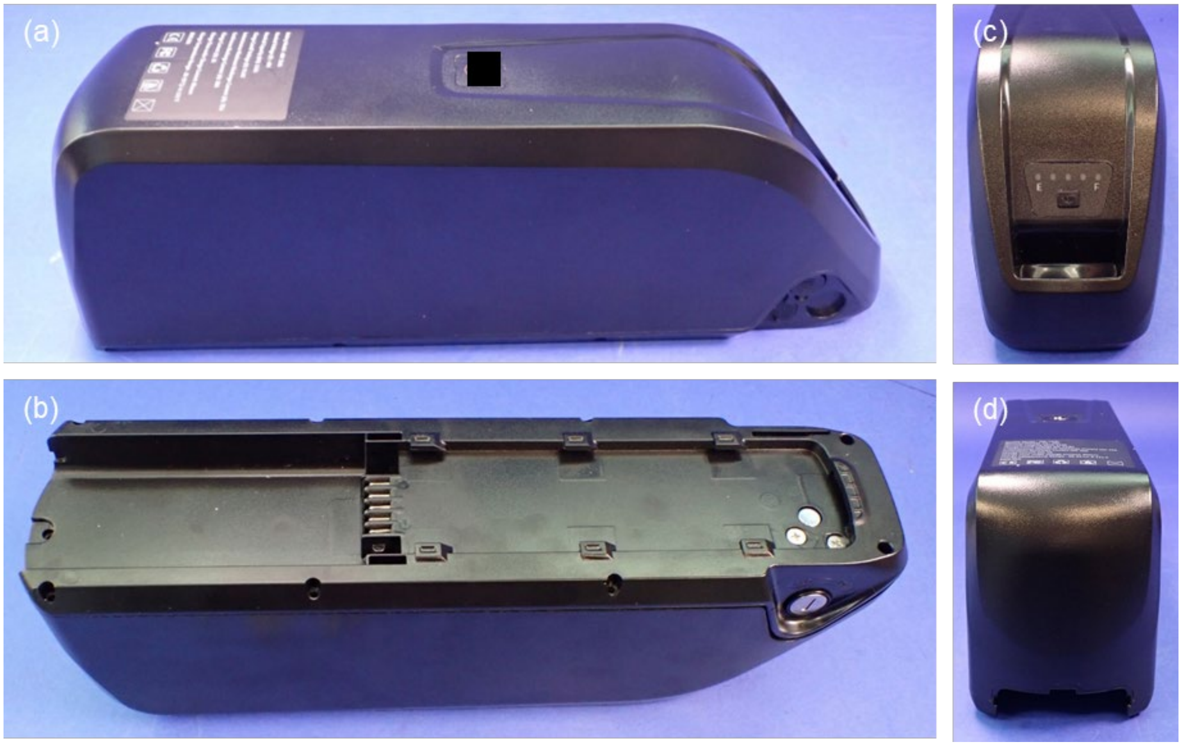


Figure A - 7. Pair 2 Rep – Pack as received; (a) side view; (b) discharge port; (c) and (d) end caps.

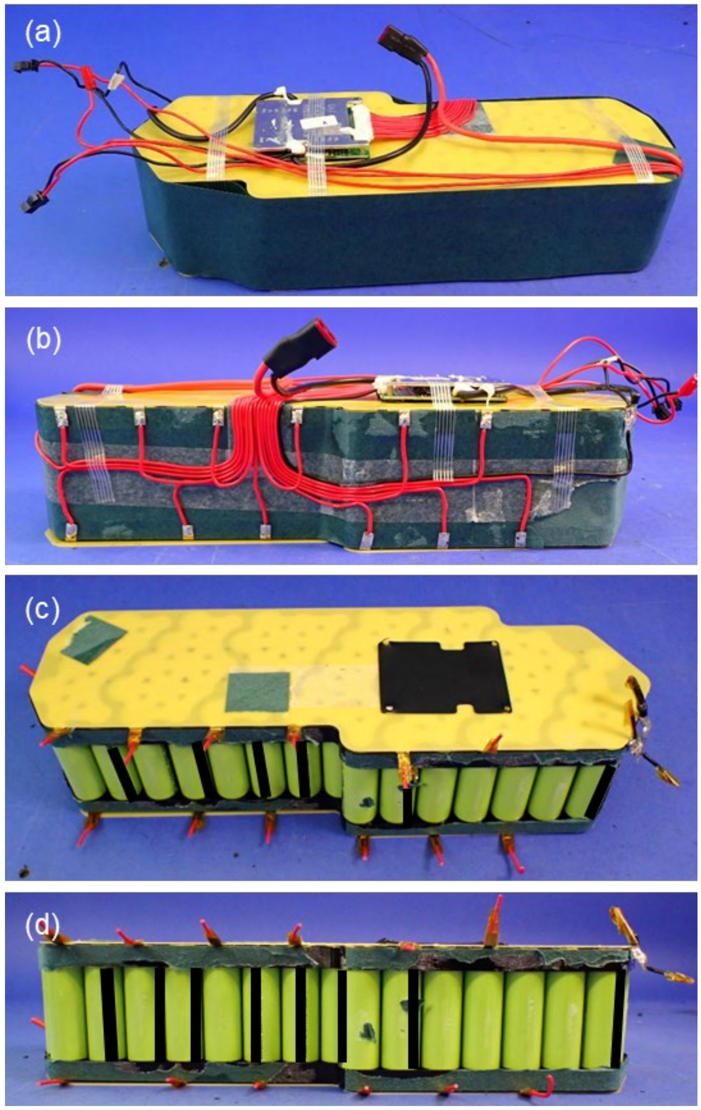


Figure A - 8. Pair 2 Rep – Pack with outer casing removed; (a) and (b) insulation and wire routing; (c) and (d) cells and insulation.

Solo – Pack

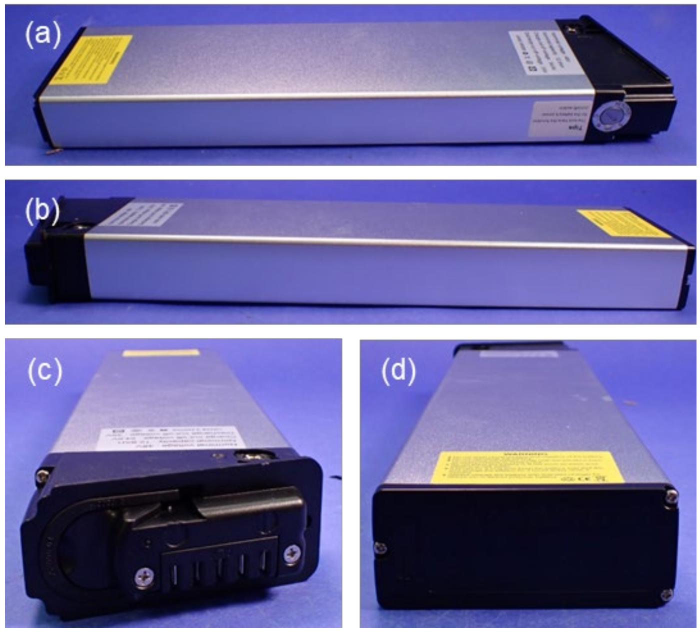


Figure A - 9. Solo – Pack as received; (a) and (b) views of side housing; (c) ignition switch and charge/discharge connectors; (d) end cap.

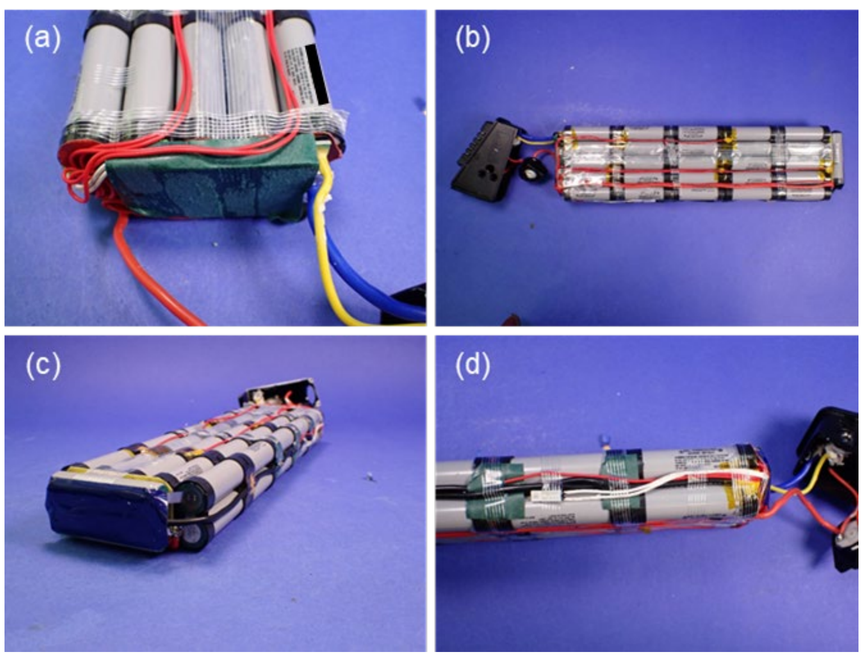


Figure A - 10. Solo – Pack with outer casing removed; (a) PCB location; (b), (c), and (d) wire routing and cell stack.

Appendix B

Pack Construction and Safety Evaluation Supplement

Pair 1 OEM – Pack (see Table 5)

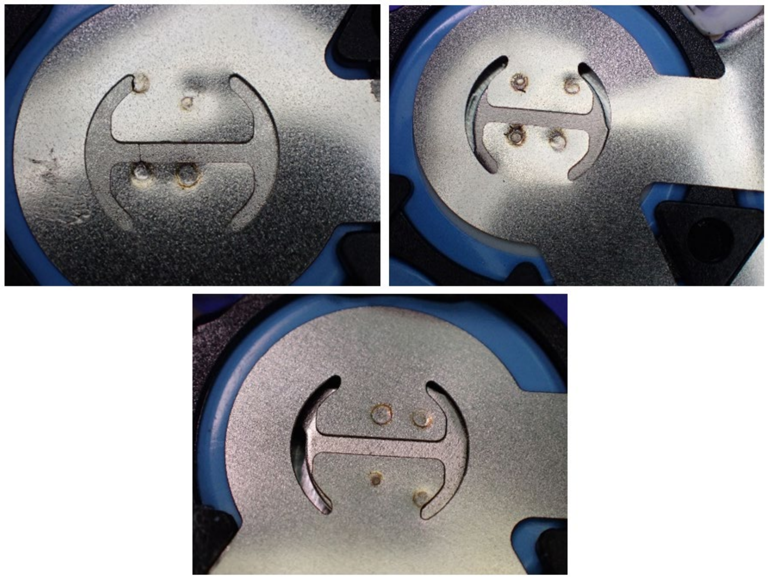


Figure B - 1. Signs of overheating and inconsistency observed on some tab welds on cell cans.

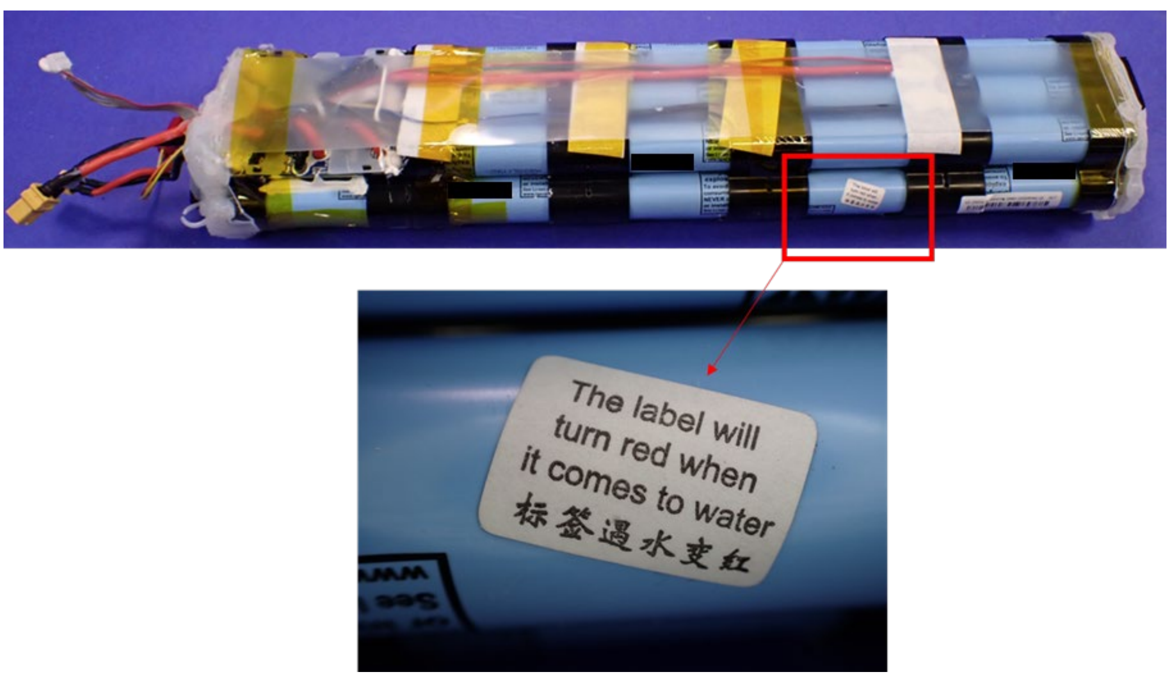


Figure B - 2. Moisture indicator paper present towards one end of the cell stack.

Pair 1 Rep – Pack (see Table 6)

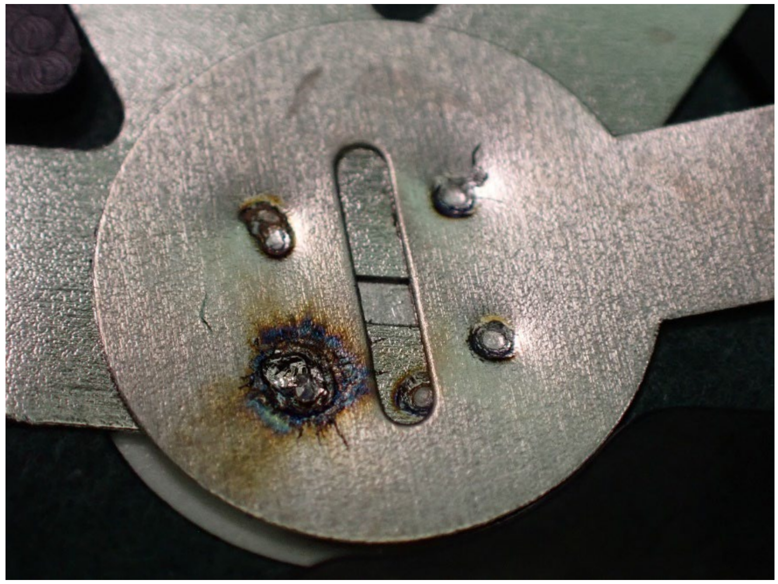


Figure B - 3. Signs of overheating observed on some tab welds on cell cans.

Figure B - 4. SOC indicator had openings that were covered only with a plastic sheet held in place with an adhesive. No gasket or seals were observed around this indicator making it prone to ingress.

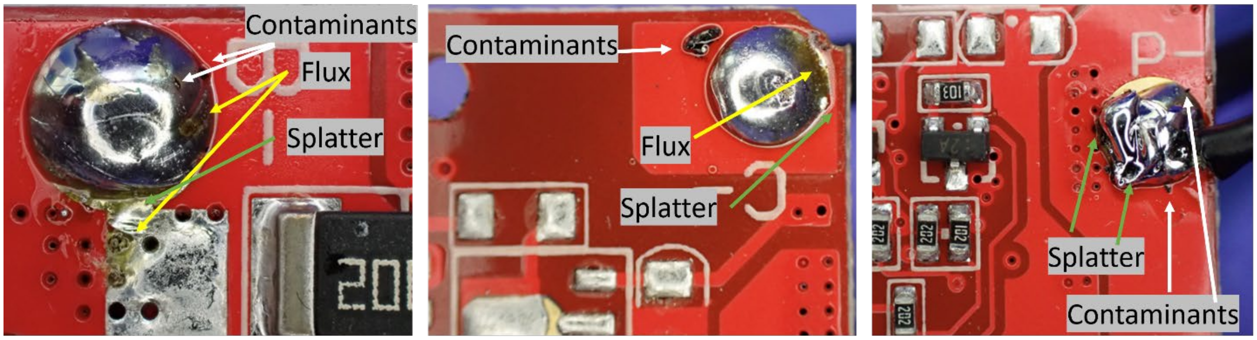


Figure B - 5. Evidence of solder splatter, contaminants, and flux observed on all PCBs.

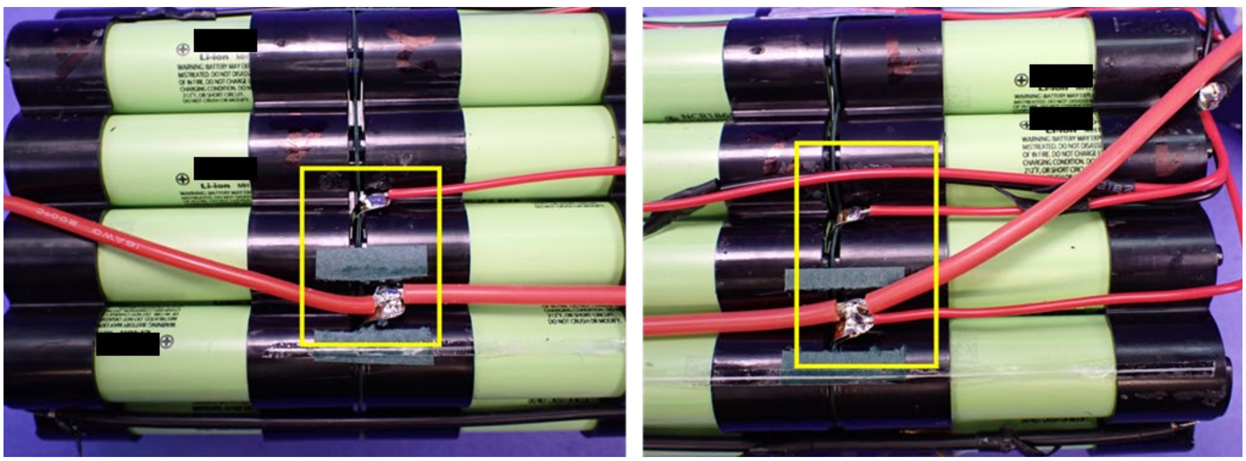


Figure B - 6. Inconsistent soldering and flux residue observed at the sense lines connection.

Pair 2 OEM – Pack (see Table 7)

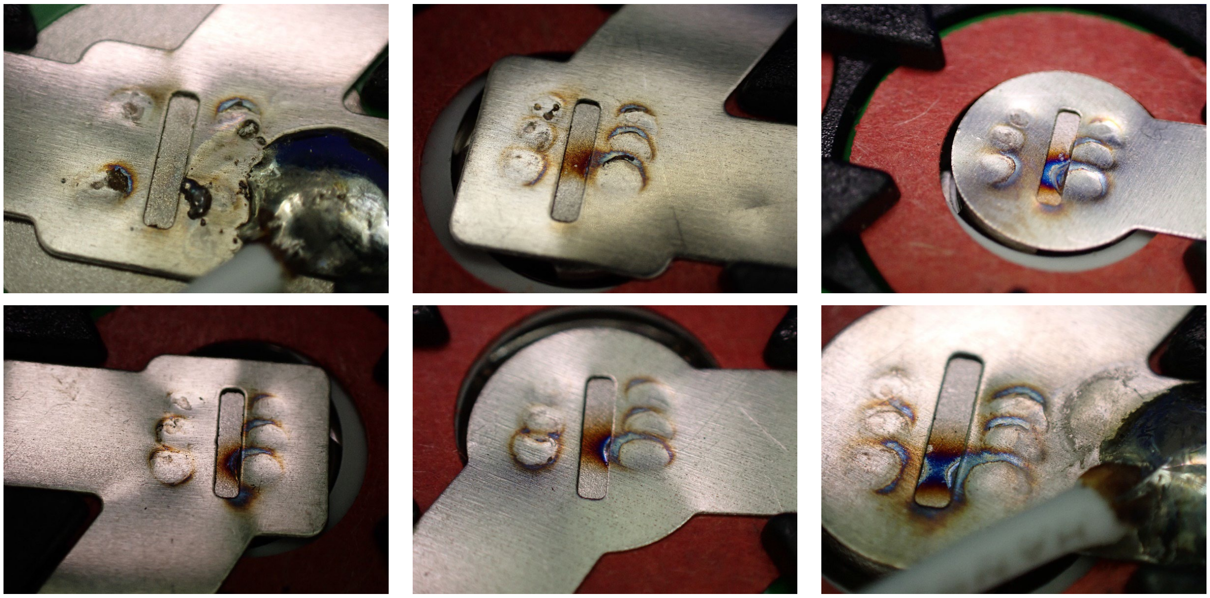


Figure B - 7.   Signs of overheating observed on some tab welds on cell cans.

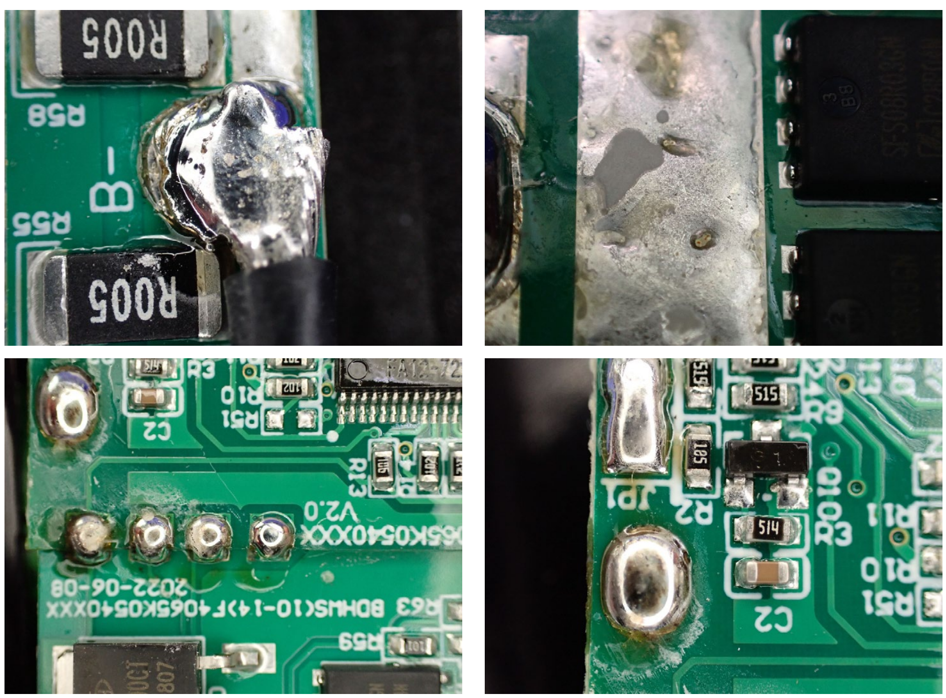


Figure B - 8.   Inconsistent soldering and flux residue observed at the sense lines connections.

Pair 2 Rep – Pack (see Table 8)

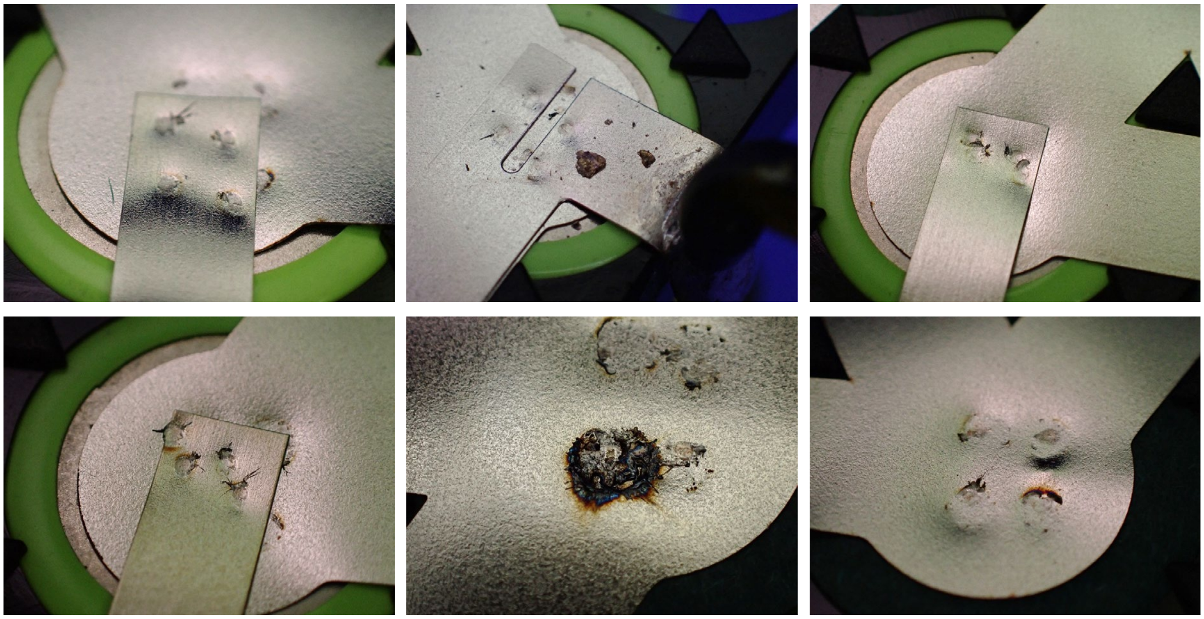


Figure B - 9. Signs of overheating observed on some tab welds on cell cans.

Figure B - 10. SOC indicator had openings that were covered only with a plastic sheet held in place with an adhesive. No gasket or seals were observed around this indicator making it prone to ingress.

Solo – Pack (see Table 9)

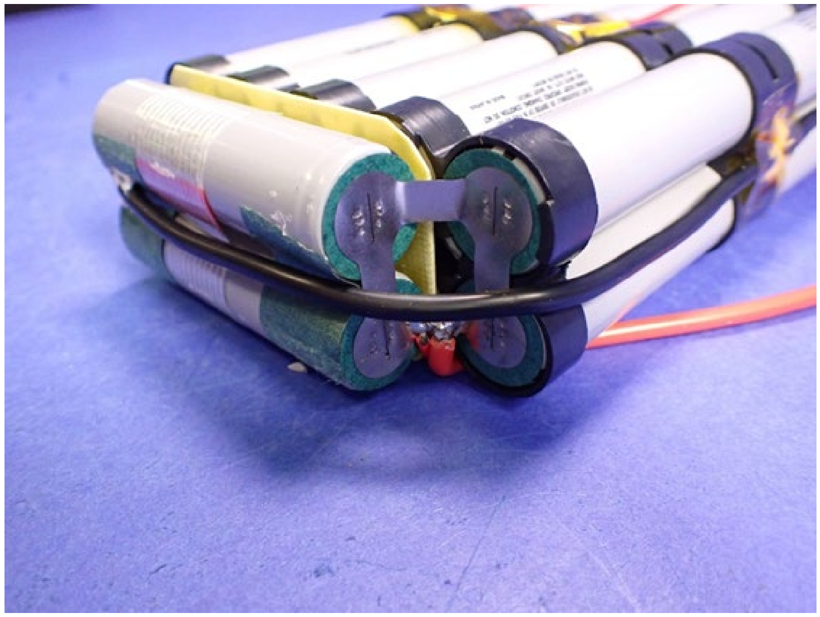


Figure B - 11. Sharp cell tabs in vicinity of cables.

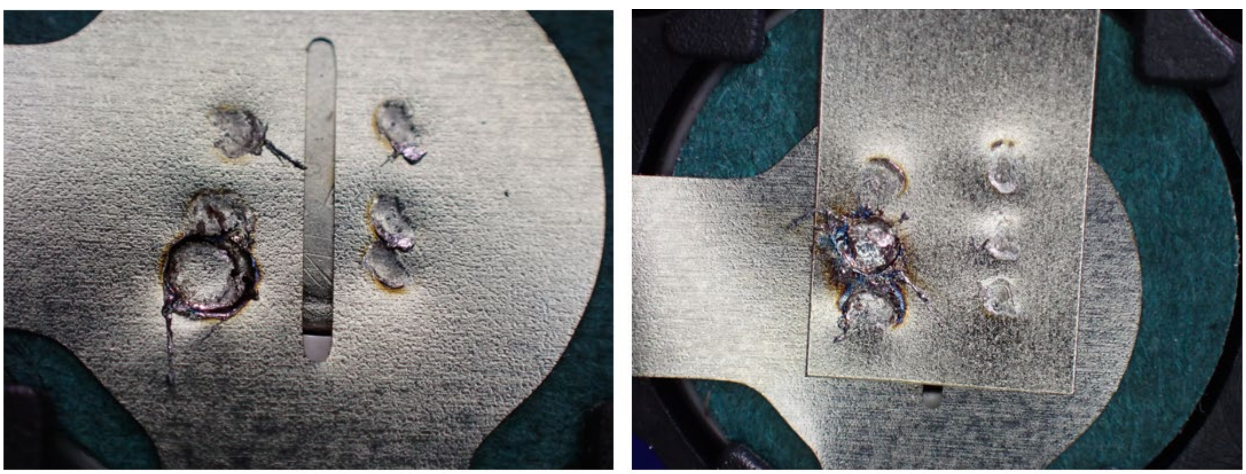


Figure B - 12. Signs of overheating observed on some tab welds on cell cans.

Plots: Charging at Ambient Temperature

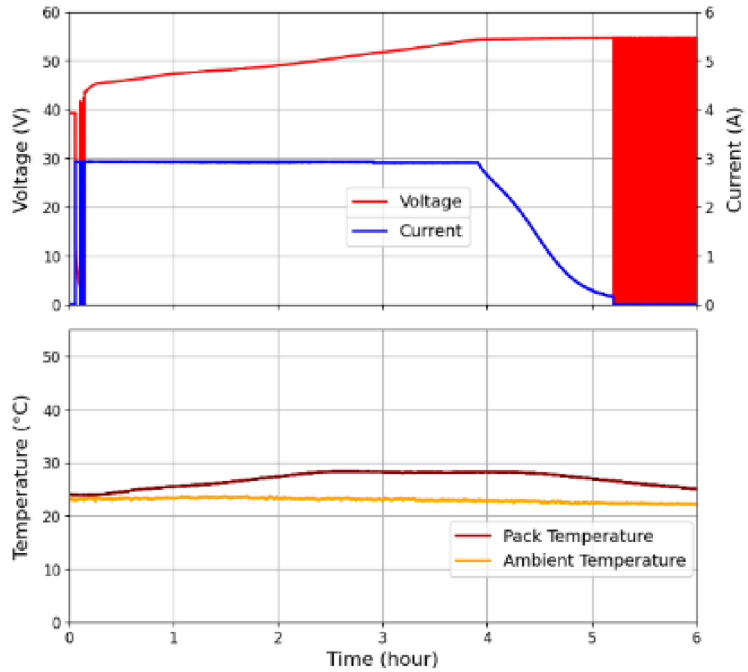


Figure B - 13. Charging of Pair 1 OEM – Pack.

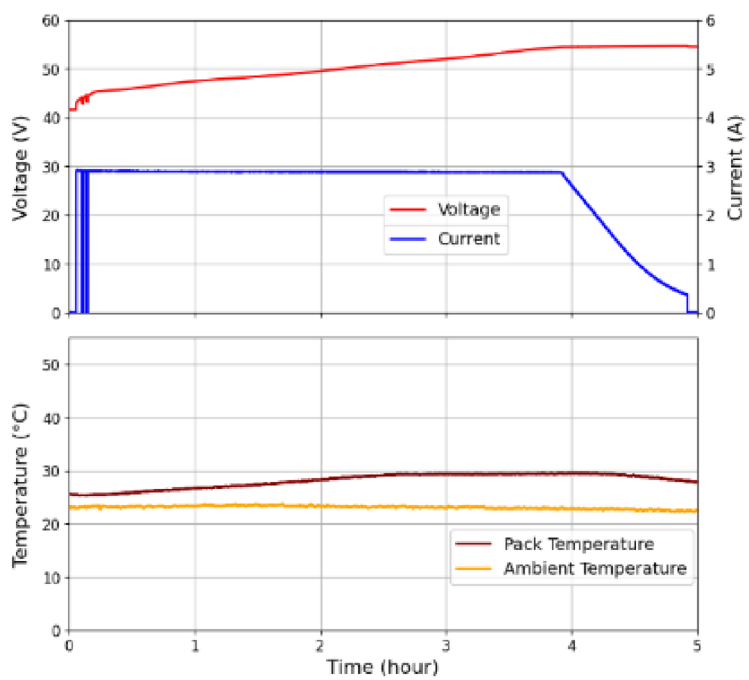


Figure B - 14. Charging of Pair 1 Rep – Pack.

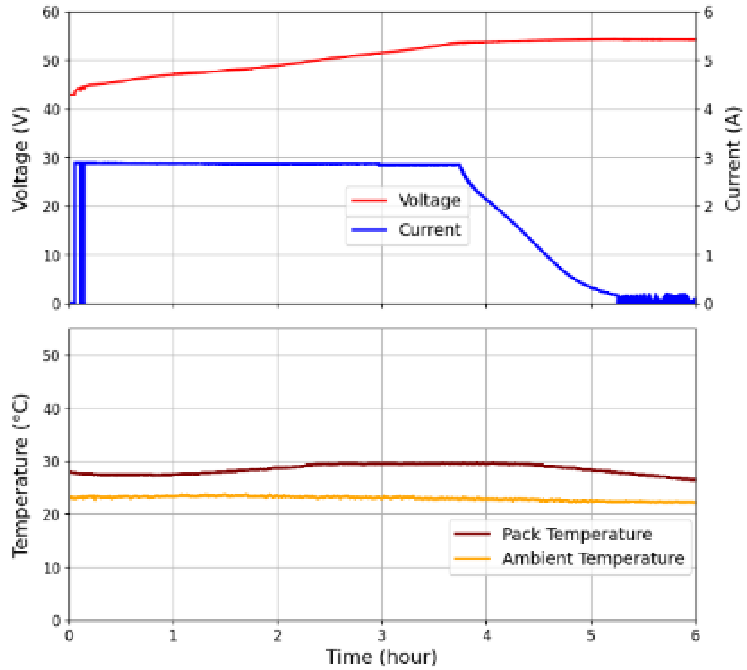


Figure B - 15. Charging of Pair 2 OEM – Pack.

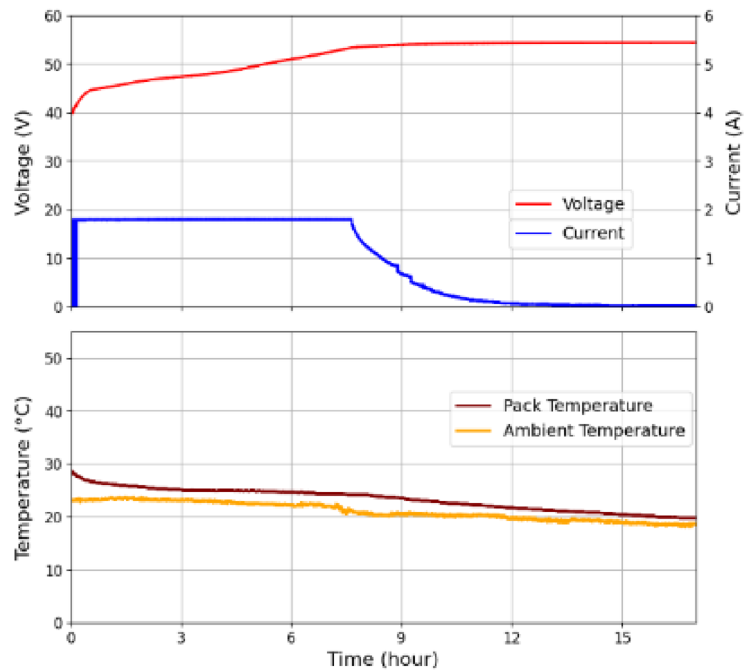


Figure B - 16. Charging of Pair 2 Rep – Pack.

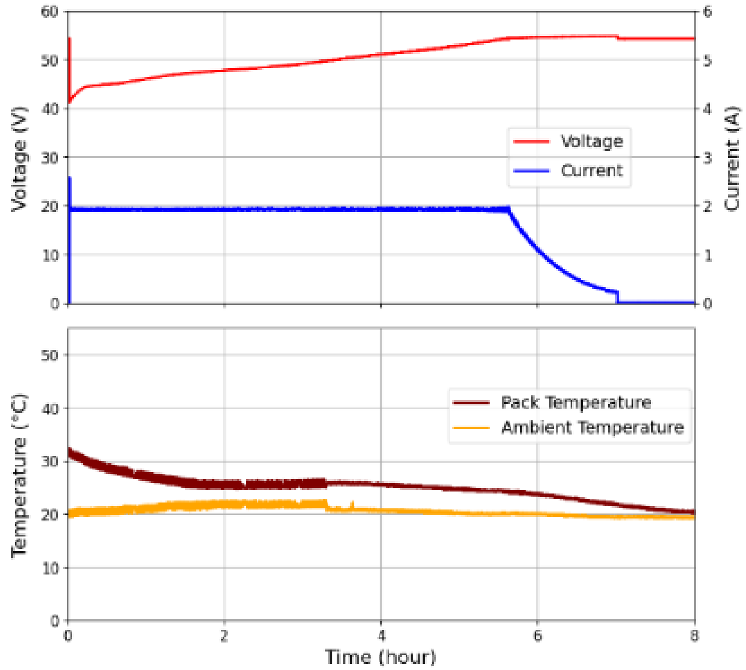


Figure B - 17. Charging of Solo – Pack.

Plots: Discharging at Ambient Temperature

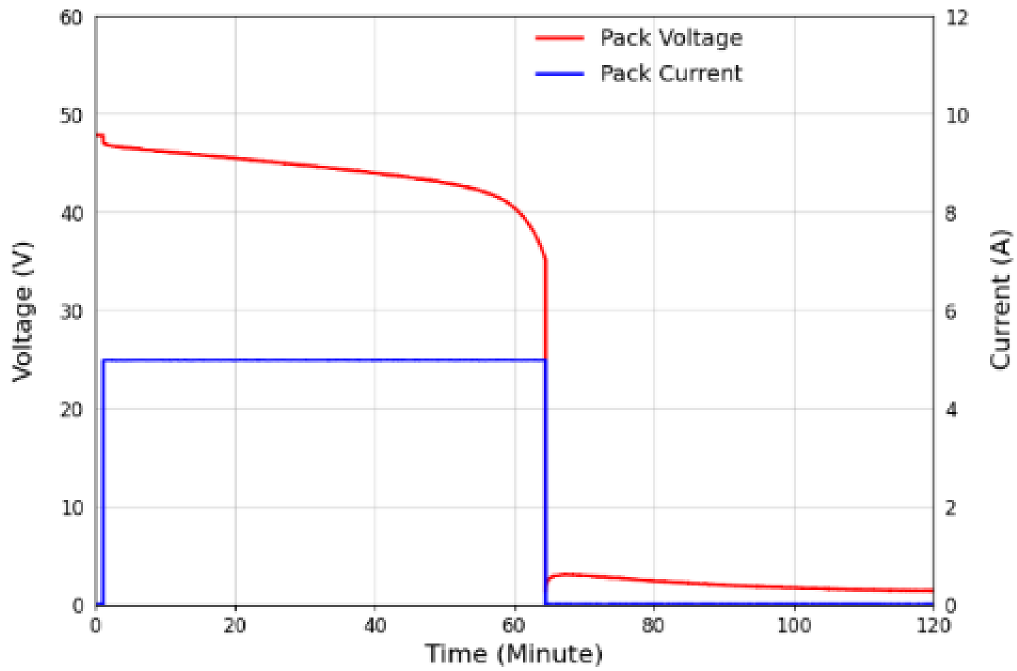


Figure B - 18. Discharging of Pair 1 OEM – Pack.

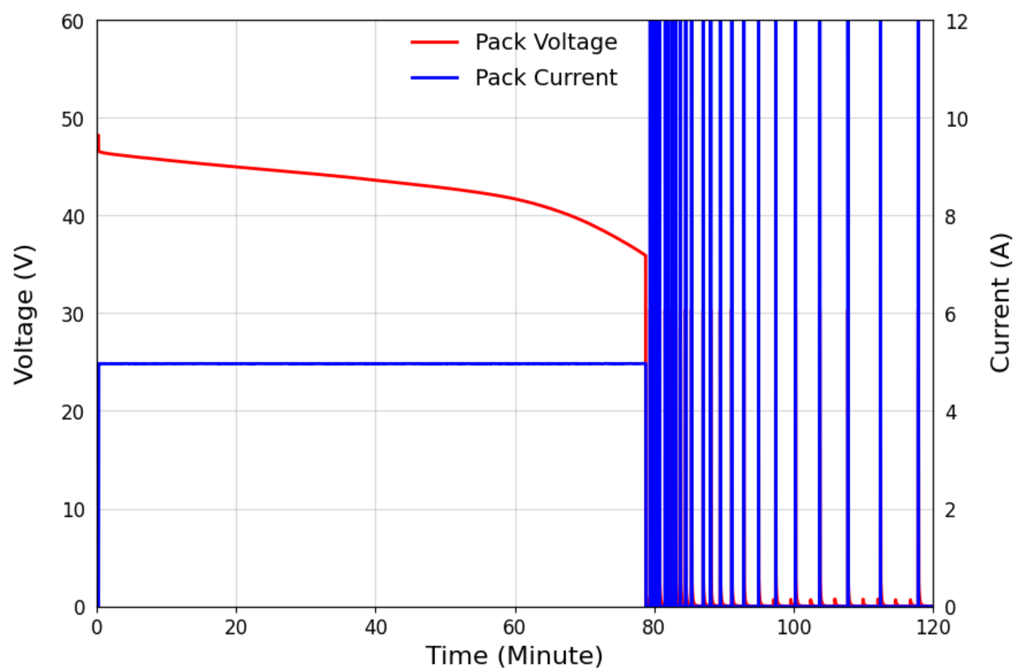


Figure B - 19 Discharging of Pair 1 Rep – Pack.

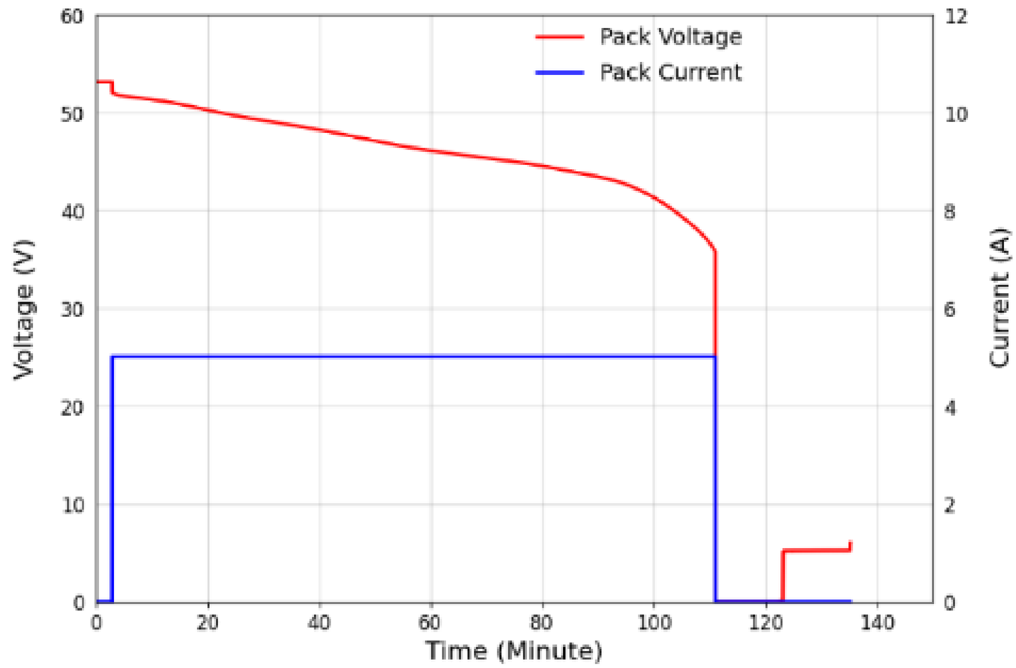


Figure B - 20. Discharging of Pair 2 OEM – Pack.

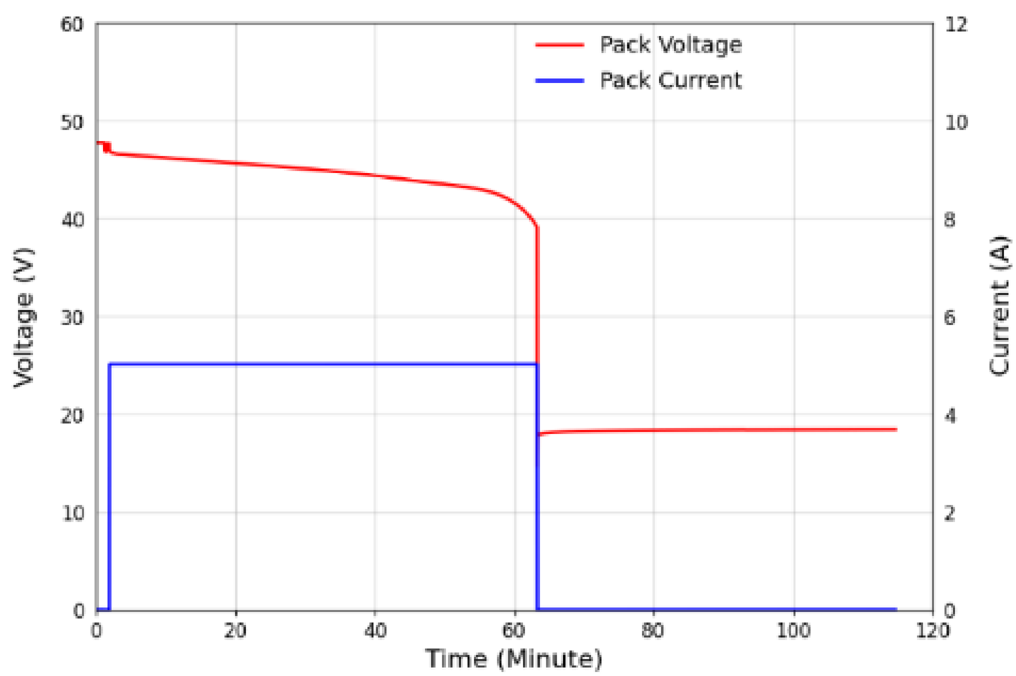


Figure B - 21. Discharging of Pair 2 Rep – Pack.

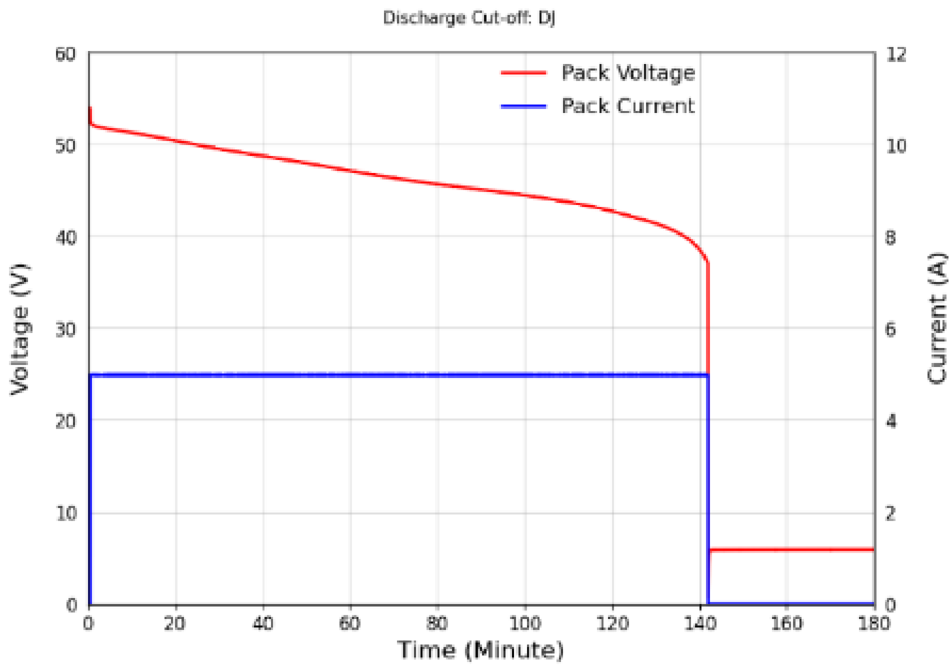


Figure B - 22. Discharging of Solo – Pack.

Plots: Overcharging at Ambient Temperature

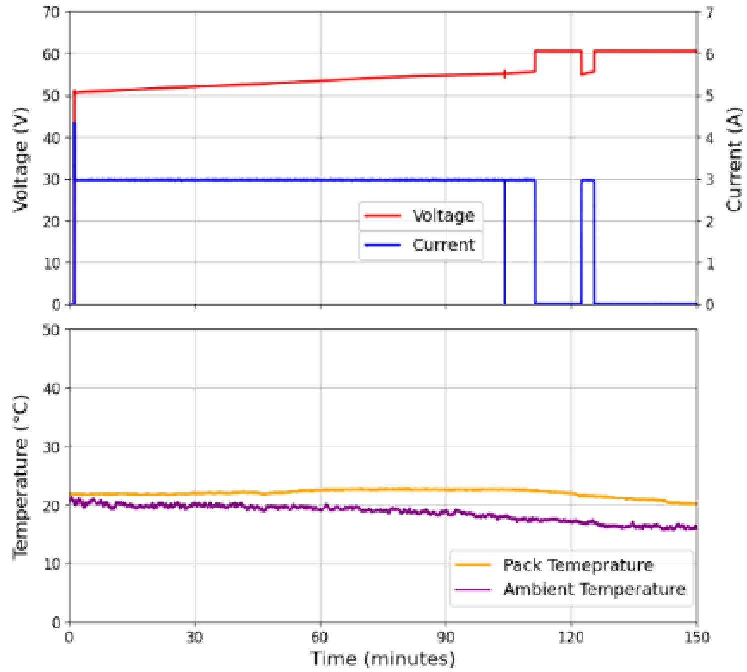


Figure B - 23. Overcharging of Pair 1 OEM – Pack.

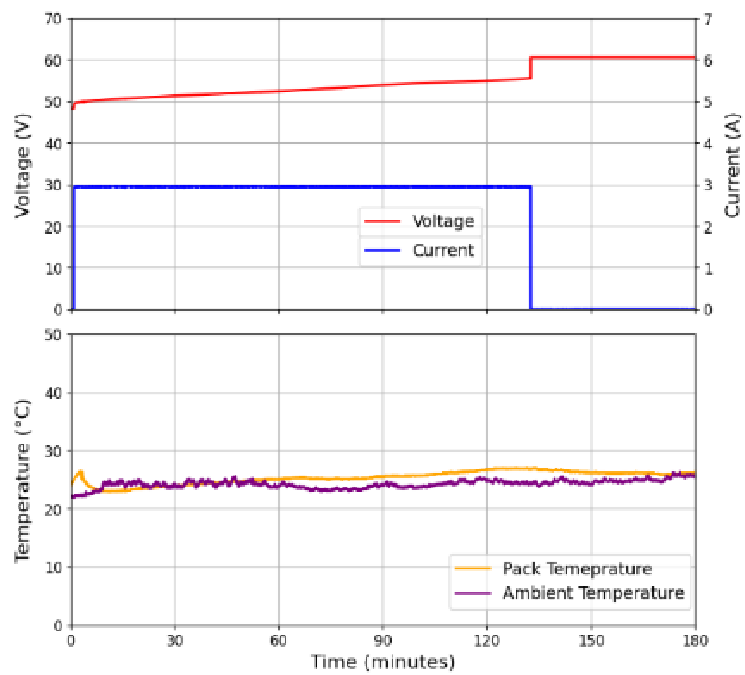


Figure B - 24. Overcharging of Pair 1 Rep – Pack.

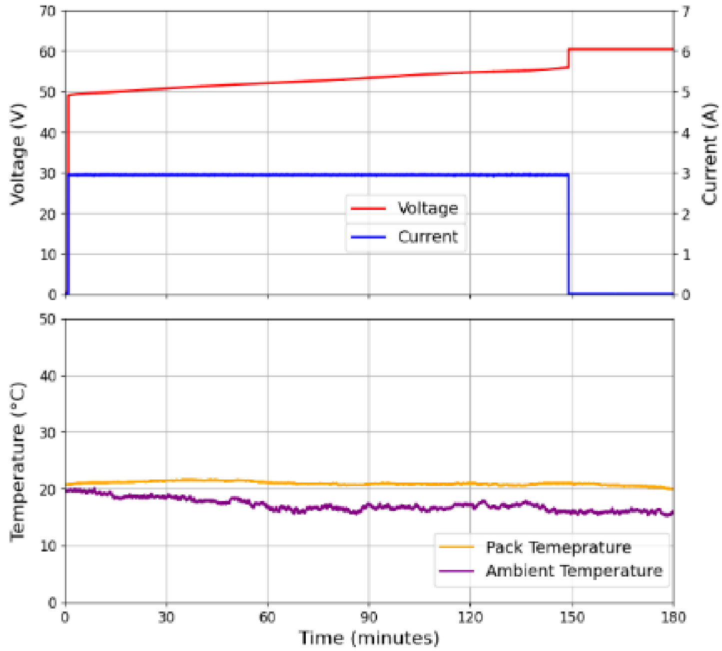


Figure B - 25. Overcharging of Pair 2 OEM – Pack.

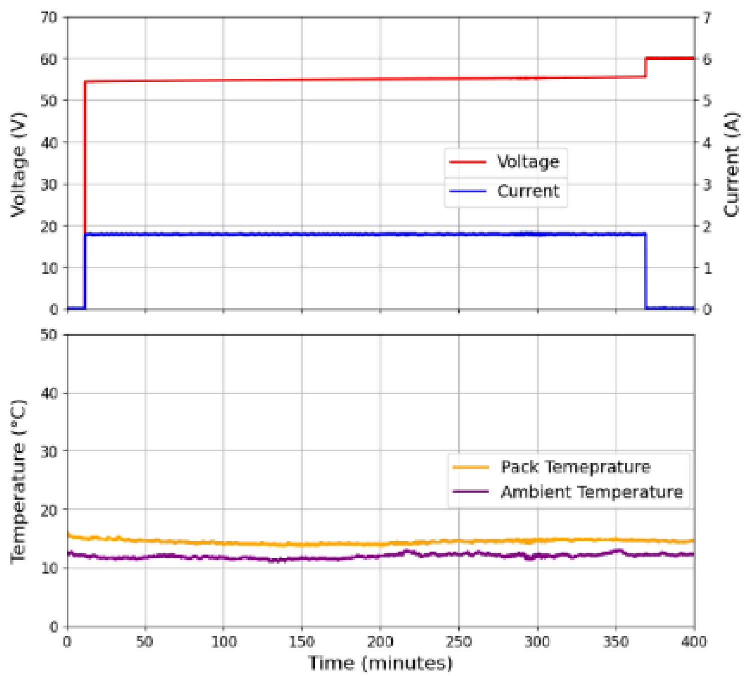


Figure B - 26. Overcharging of Pair 2 Rep – Pack.

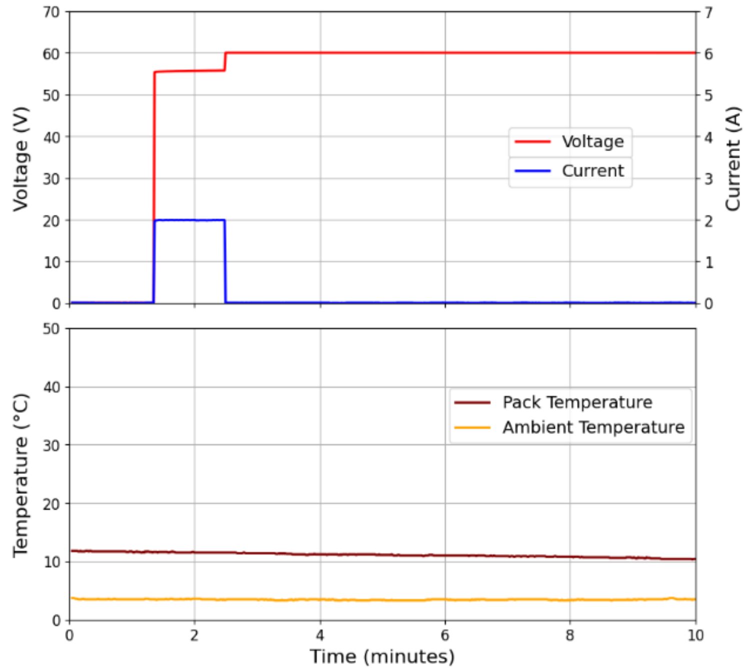


Figure B - 27. Overcharging of Solo – Pack.

Plots: Maximum Allowable Temperature

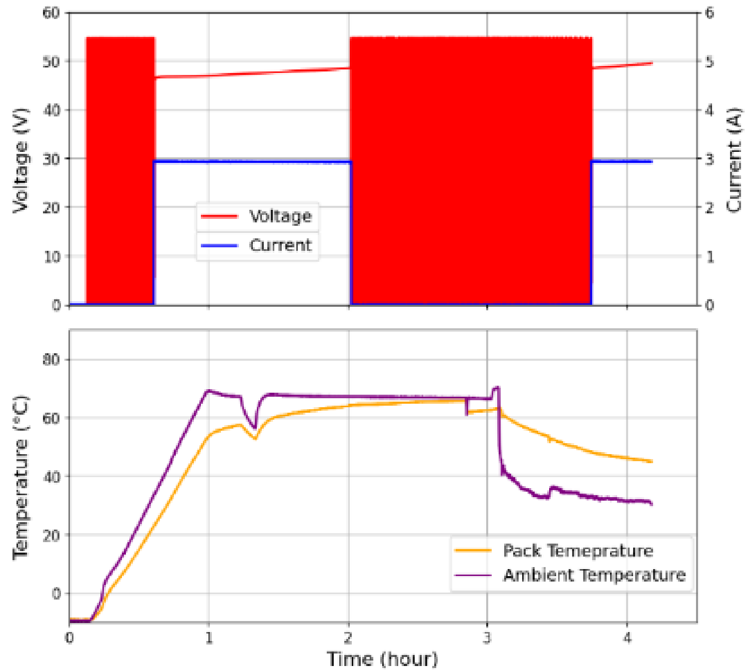


Figure B - 28. Allowable temperature charging of Pair 1 OEM – Pack.

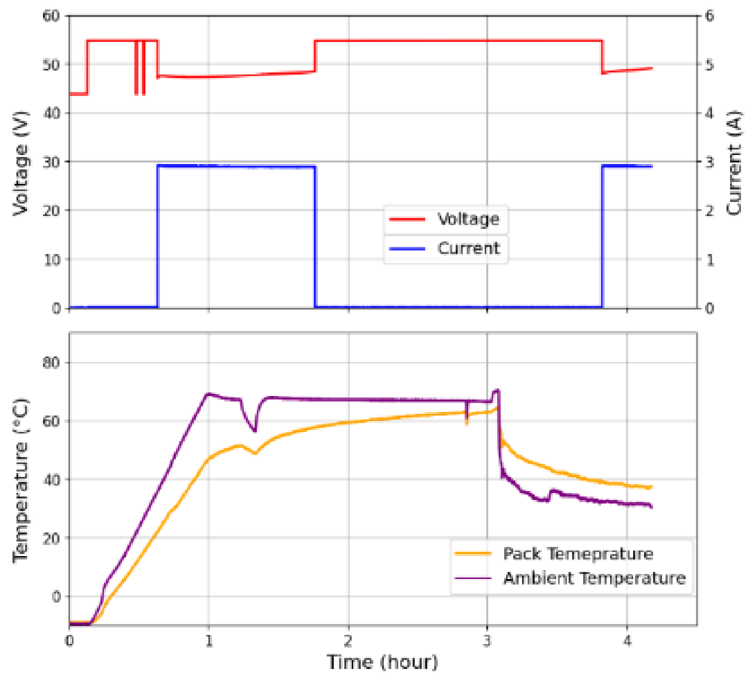


Figure B - 29. Allowable temperature charging of Pair 1 Rep – Pack.

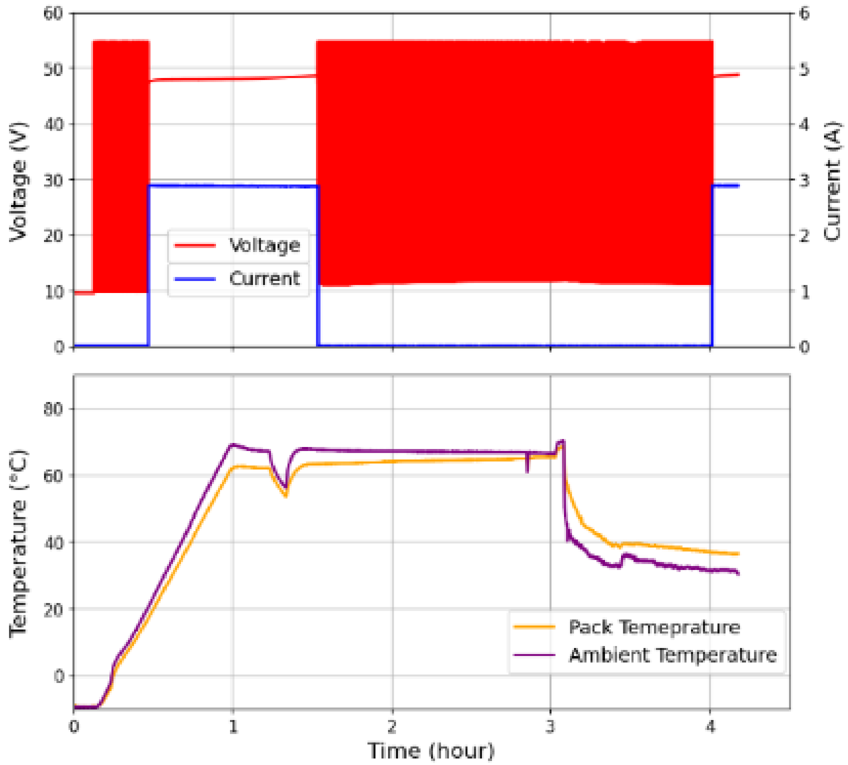


Figure B - 30. Allowable temperature charging of Pair 2 OEM – Pack.

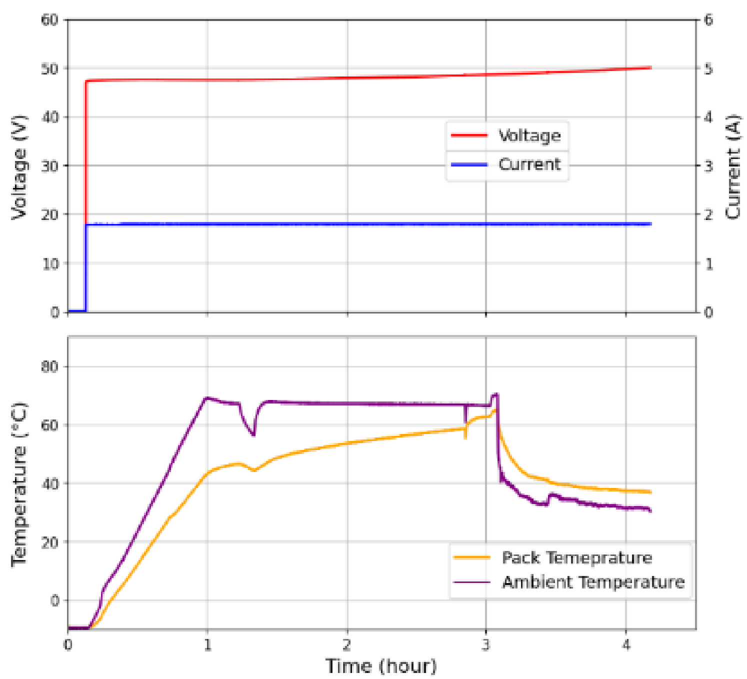


Figure B - 31. Allowable temperature charging of Pair 2 Rep – Pack.

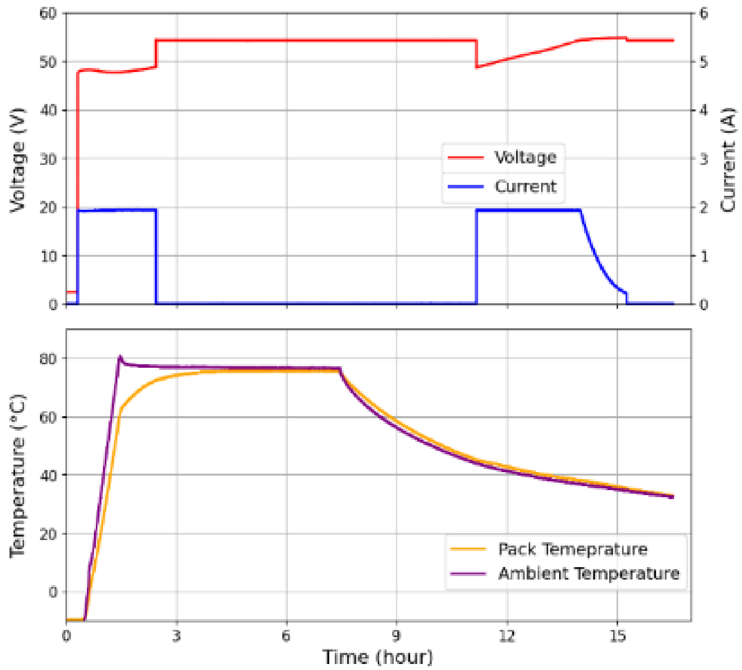


Figure B - 32. Allowable temperature charging of Solo – Pack.

Plots: Short-circuit Testing

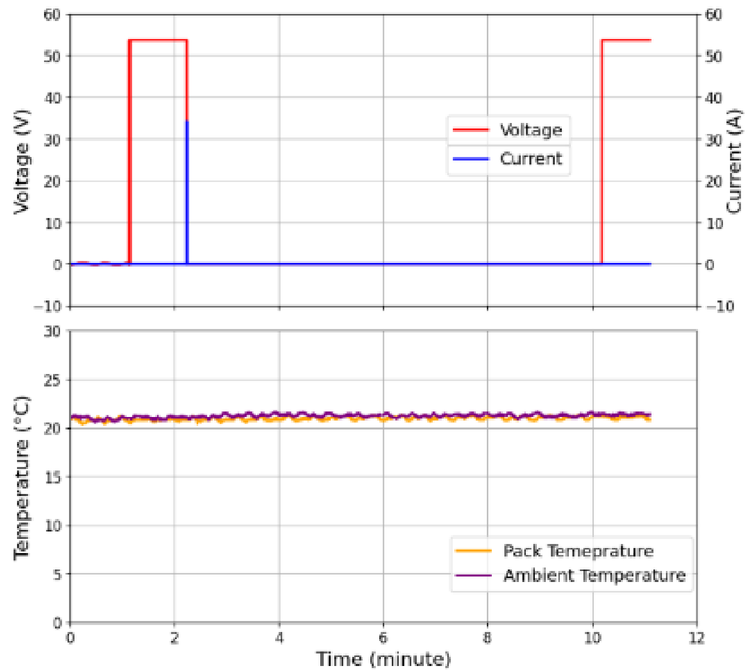


Figure B - 33. Short-circuit testing of Pair 1 OEM – Pack.

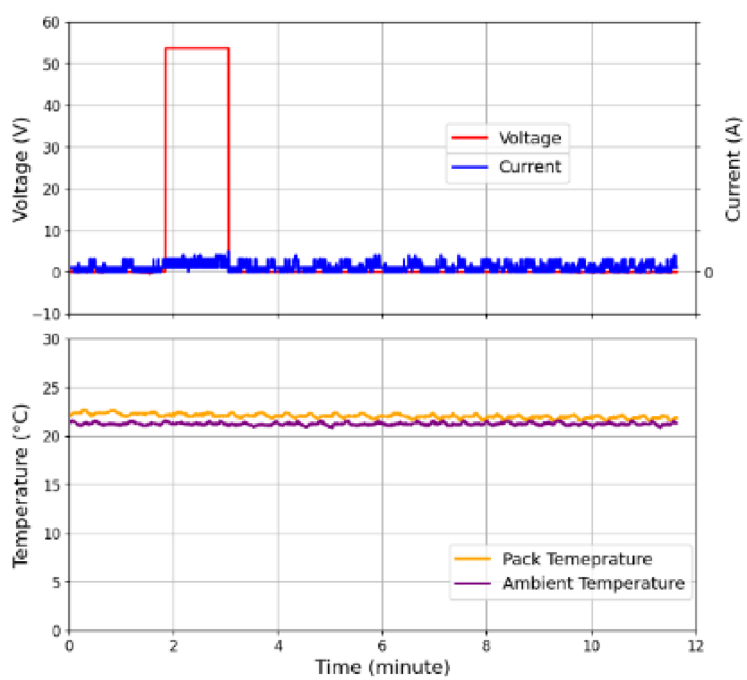


Figure B - 34. Short-circuit testing of Pair 1 Rep – Pack.

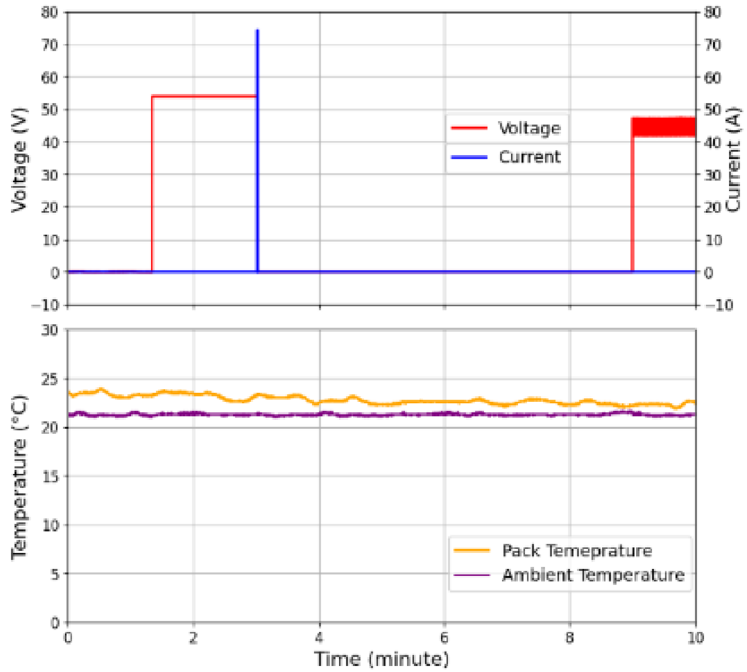


Figure B - 35. Short-circuit testing of Pair 2 OEM – Pack.

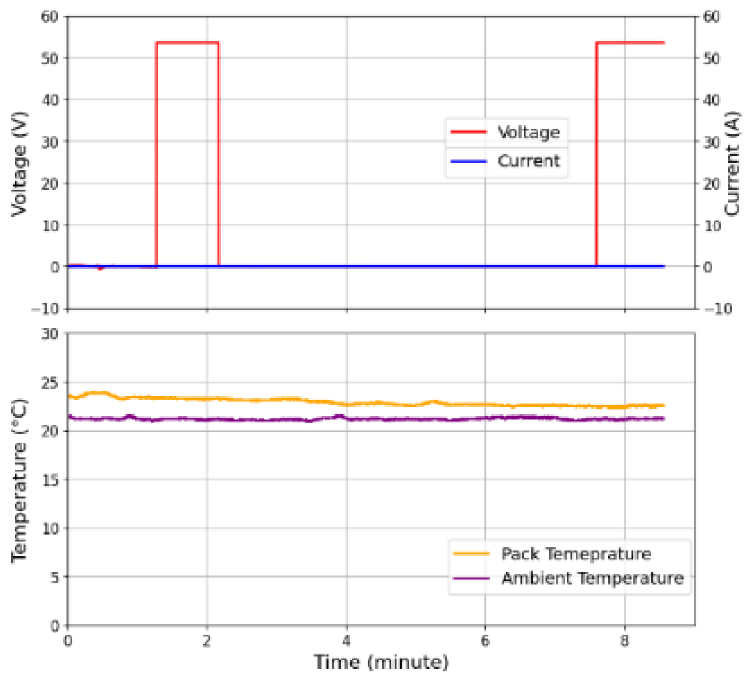


Figure B - 36. Short-circuit testing of Pair 2 Rep – Pack.

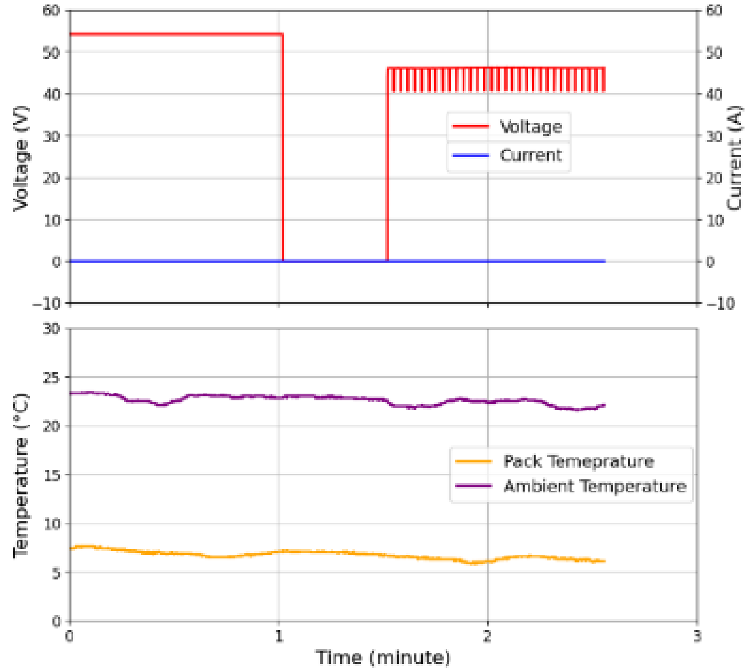


Figure B - 37. Short-circuit testing of Solo – Pack.

0% SOC Disassembly and SEM

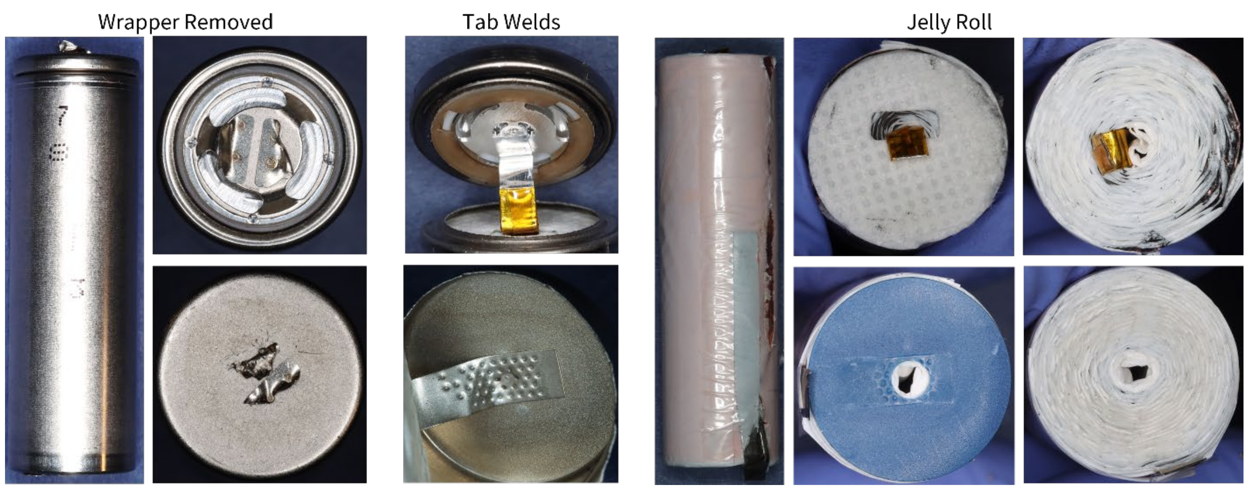


Figure B - 38. Pair 1 OEM disassembly and cell construction overview.

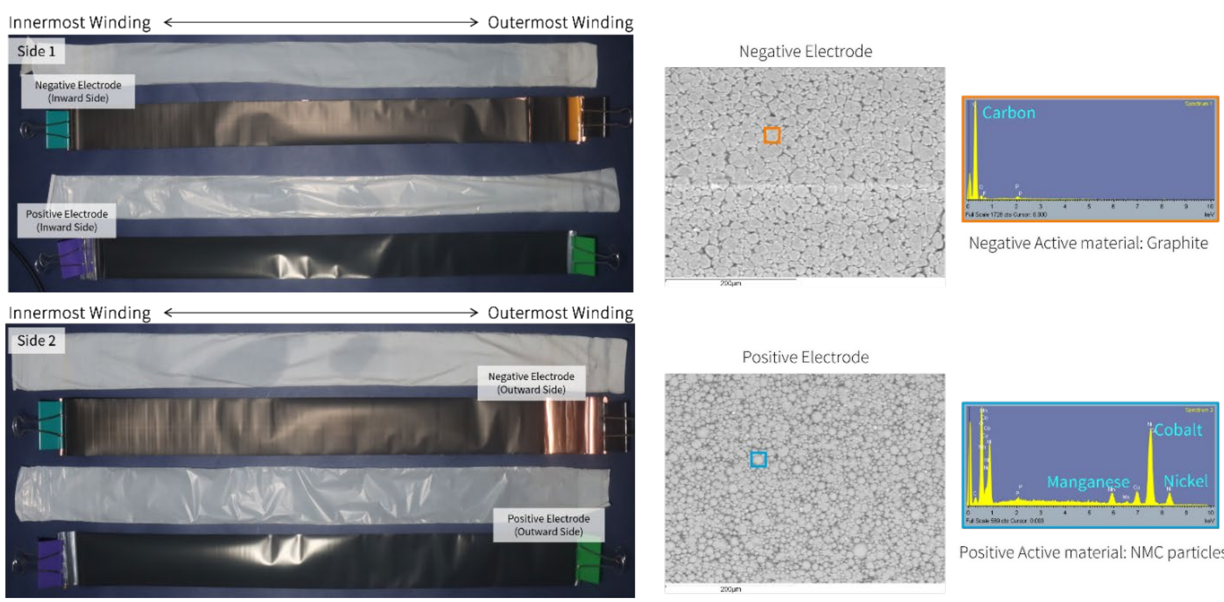


Figure B - 39. Pair 1 OEM – Pack disassembly and compositions of electrodes.

Figure B - 40. Pair 1 Rep – Pack disassembly and cell construction overview.

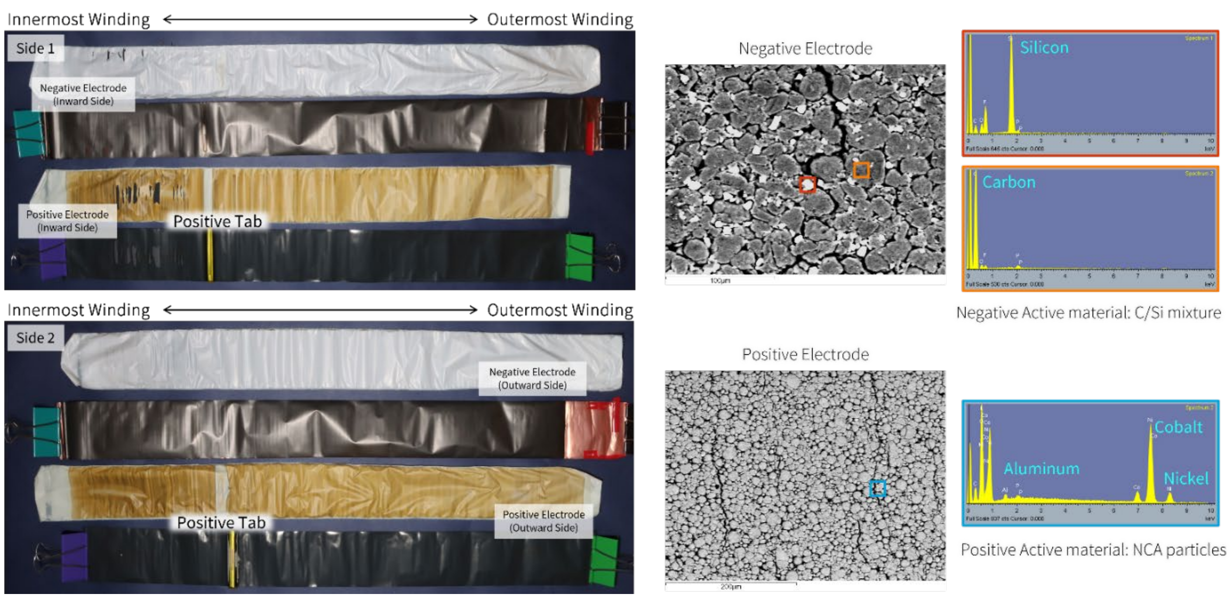


Figure B - 41. Pair 1 Rep – Pack disassembly and compositions of electrodes.

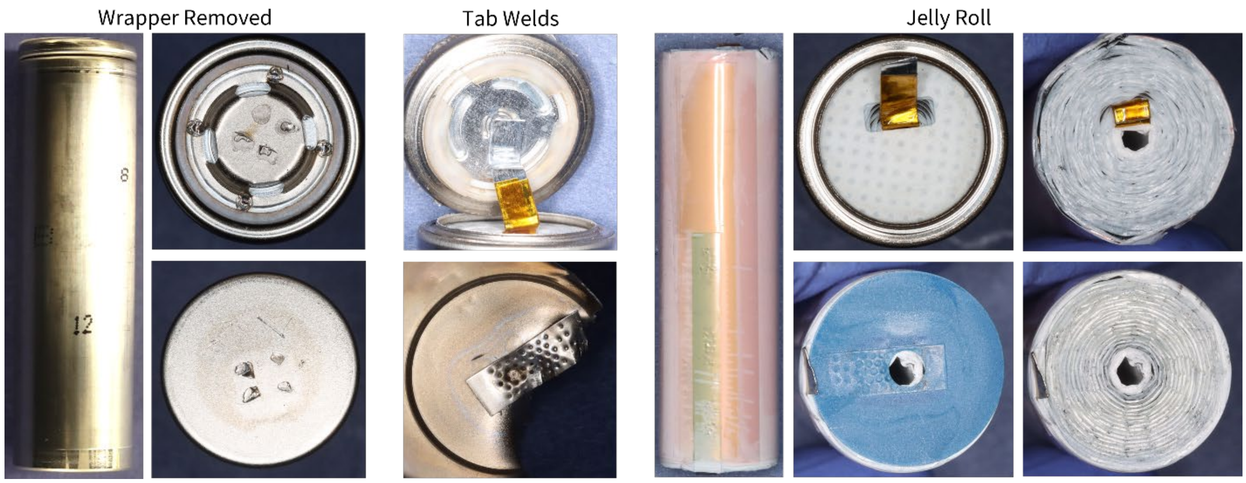


Figure B - 42. Pair 2 OEM – Pack disassembly and cell construction overview.

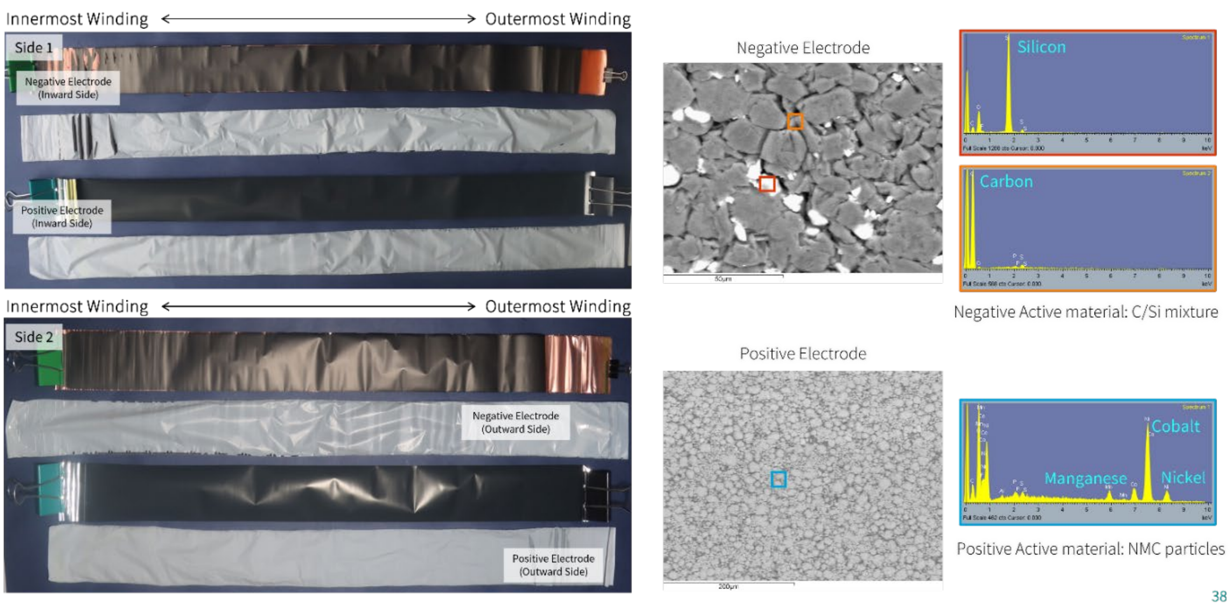


Figure B - 43. Pair 2 OEM – Pack disassembly and compositions of electrodes.

Figure B - 44. Pair 2 Rep – Pack disassembly and cell construction overview.

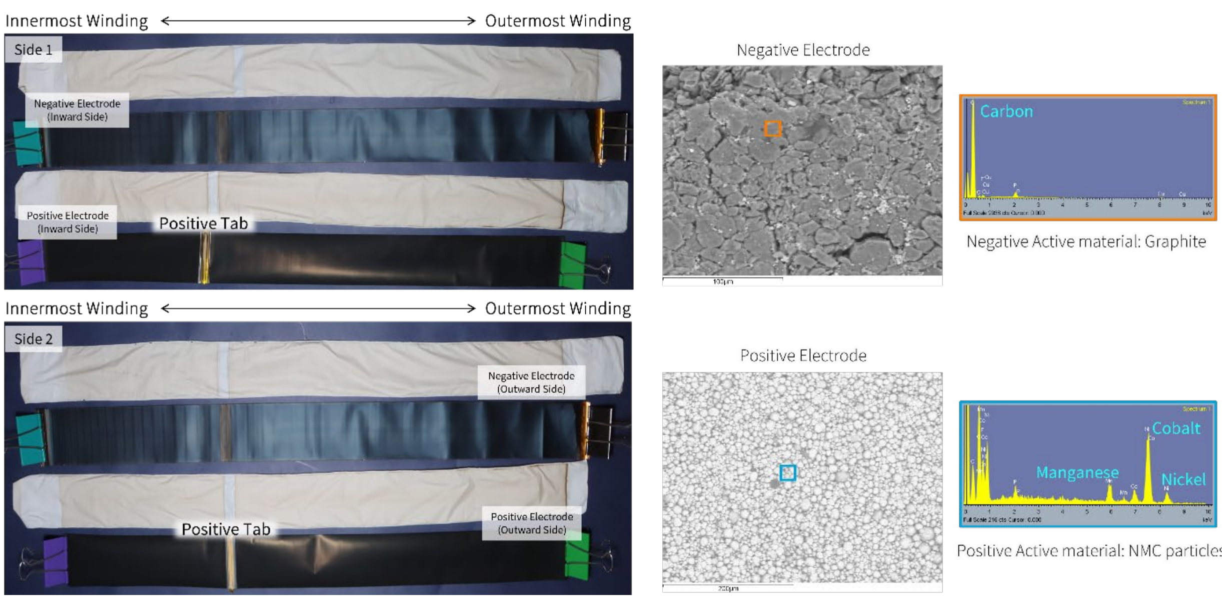


Figure B - 45. Pair 2 Rep – Pack disassembly and compositions of electrodes.

Figure B - 46. Solo – Pack disassembly and cell construction overview.

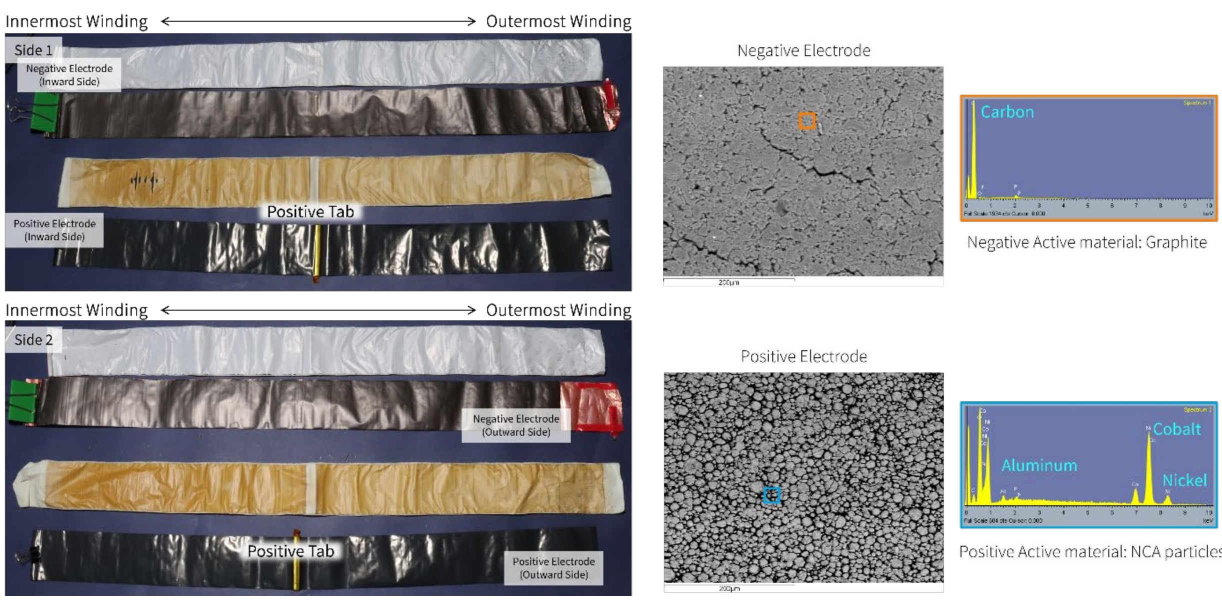


Figure B - 47. Solo – Pack disassembly and compositions of electrodes.

100% SOC Disassembly

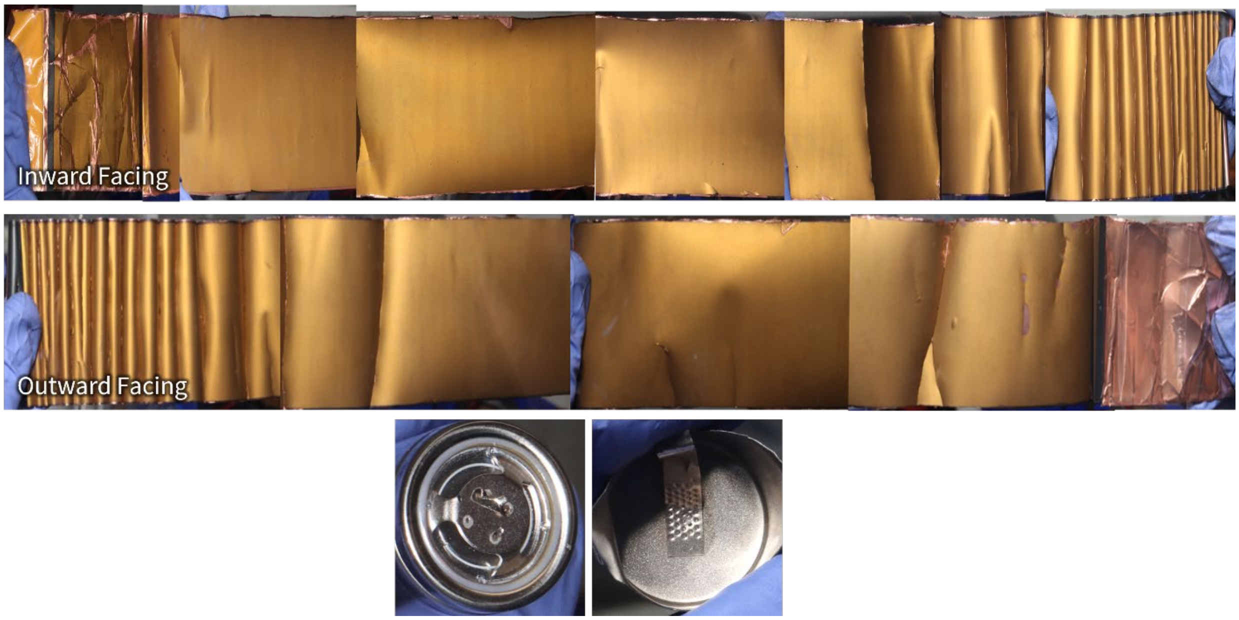


Figure B - 48. Pair 1 OEM – Pack disassembly at 100% SOC; negative electrodes are shown.

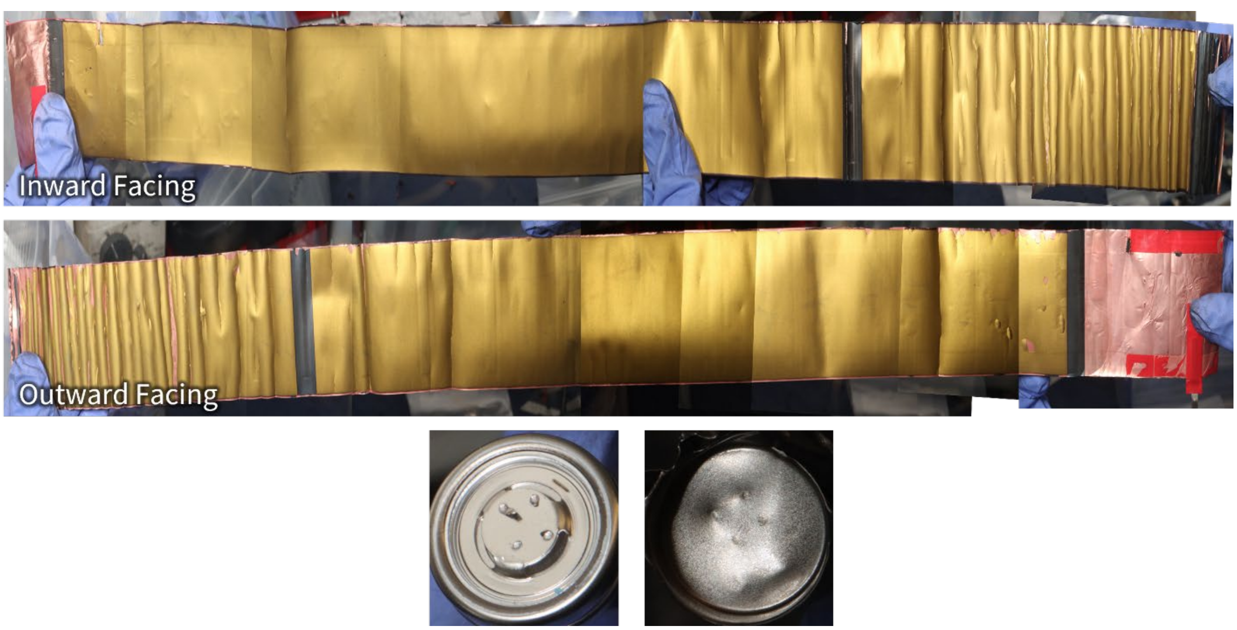


Figure B - 49. Pair 1 Rep – Pack disassembly at 100% SOC; negative electrodes are shown.

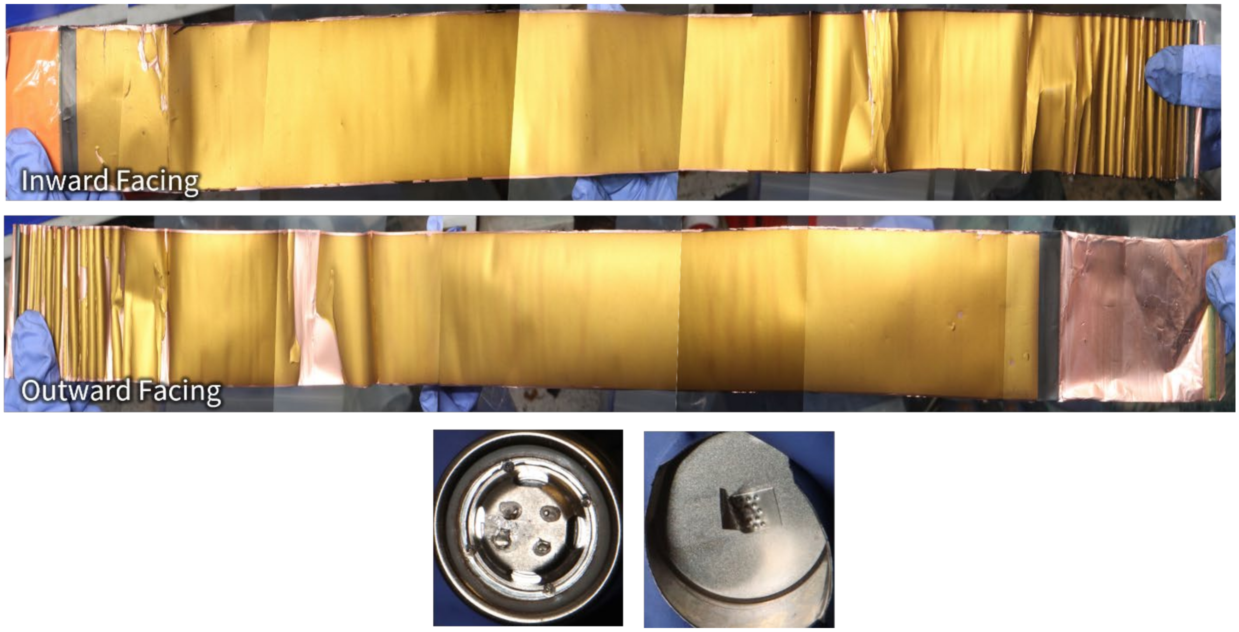


Figure B - 50. Pair 2 OEM – Pack disassembly at 100% SOC; Negative electrodes are shown.

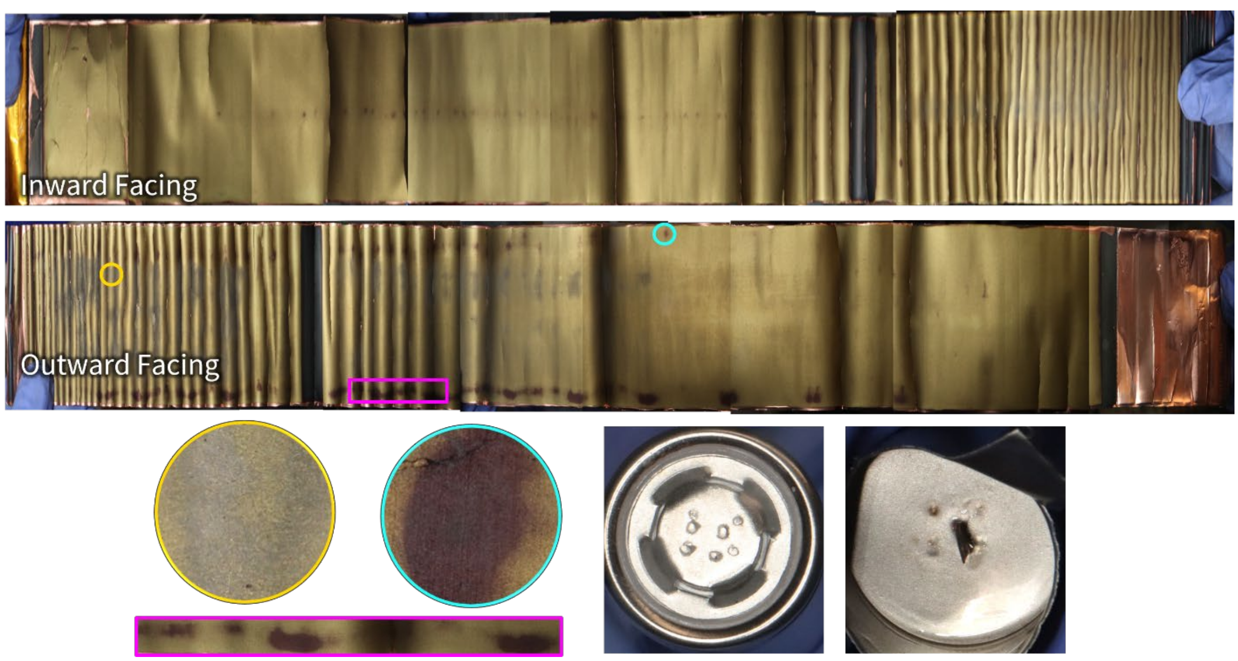


Figure B - 51. Pair 2 Rep – Pack disassembly at 100% SOC; negative electrodes are shown. Cyan and fuchsia zoom-ins show examples of underlithiation. The yellow zoom-in shows an example of alumina transfer from the separator.

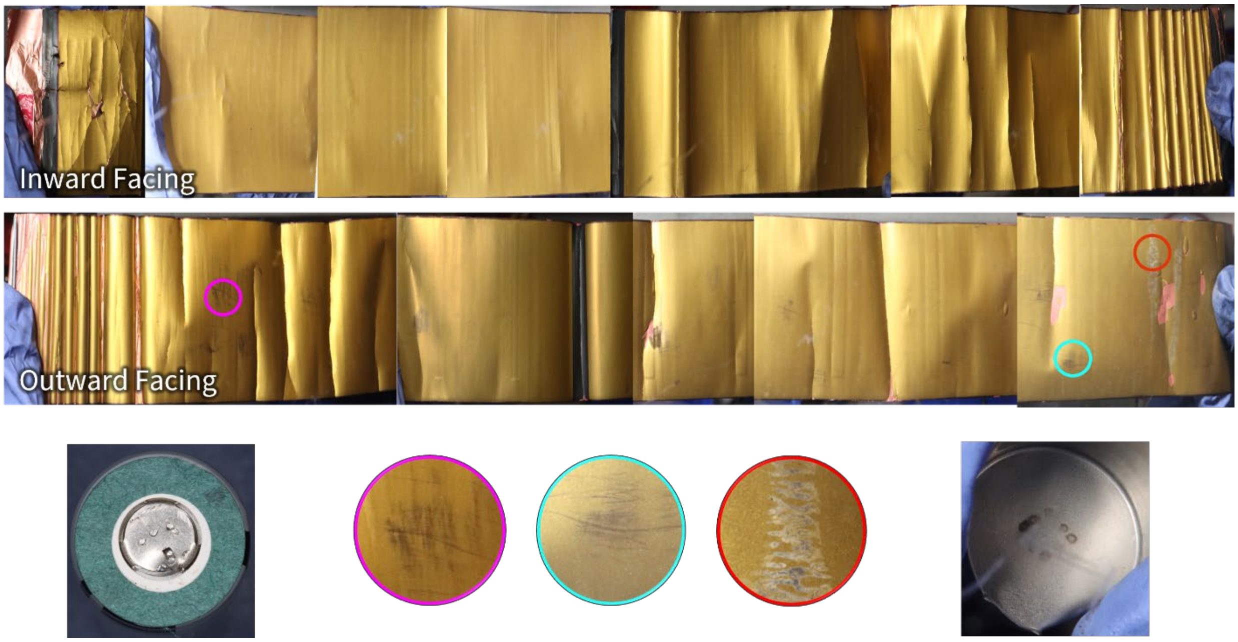


Figure B - 52. Solo – Pack disassembly at 100% SOC; negative electrodes are shown. Red zoom-in shows an example of lithium plating on the electrode while the fuchsia and cyan zoom-ins show examples of scratching at the active material surface.

CT Analysis

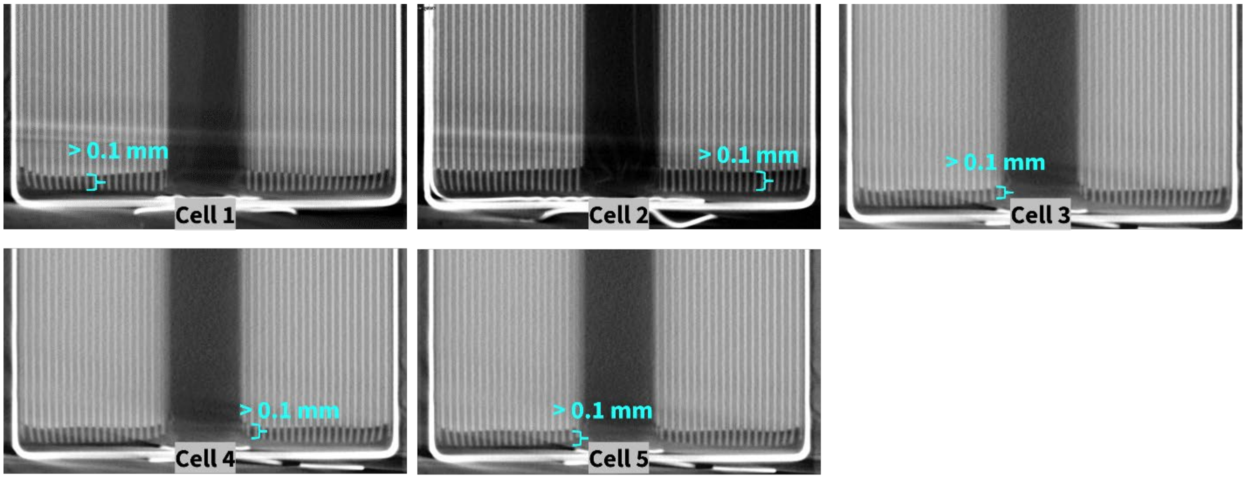


Figure B - 53. Pair 1 OEM – Pack overlap measurements. The shortest overlap of the positive electrode by the negative electrode was measured to be above 0.1 mm as is recommended by IEEE 1725.

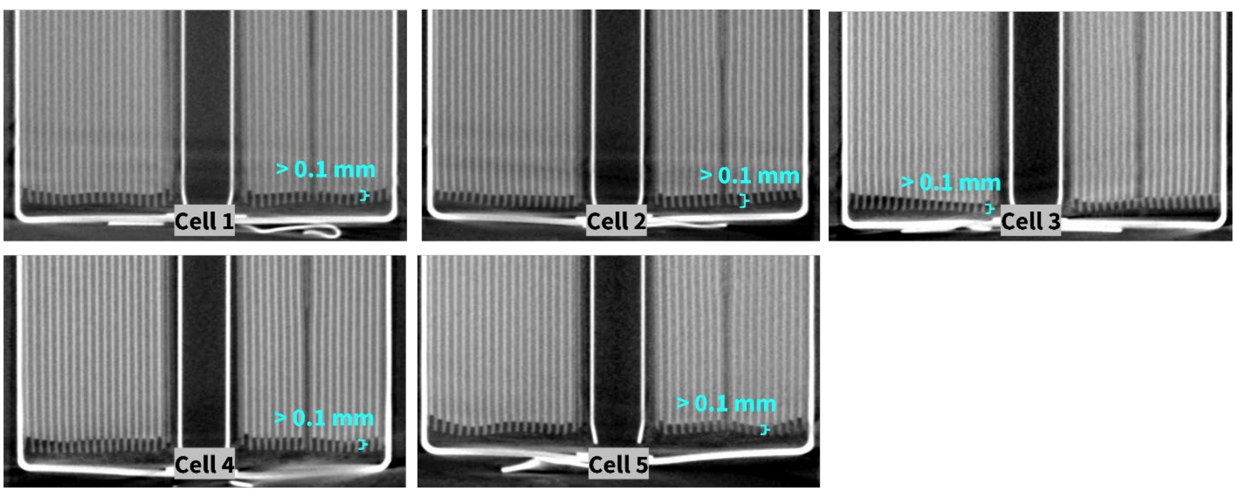


Figure B - 54. Pair 1 Rep – Pack overlap measurements. The shortest overlap region of the positive electrode by the negative electrode was measured to be above 0.1 mm industry recommendation as is recommended by IEEE 1725.

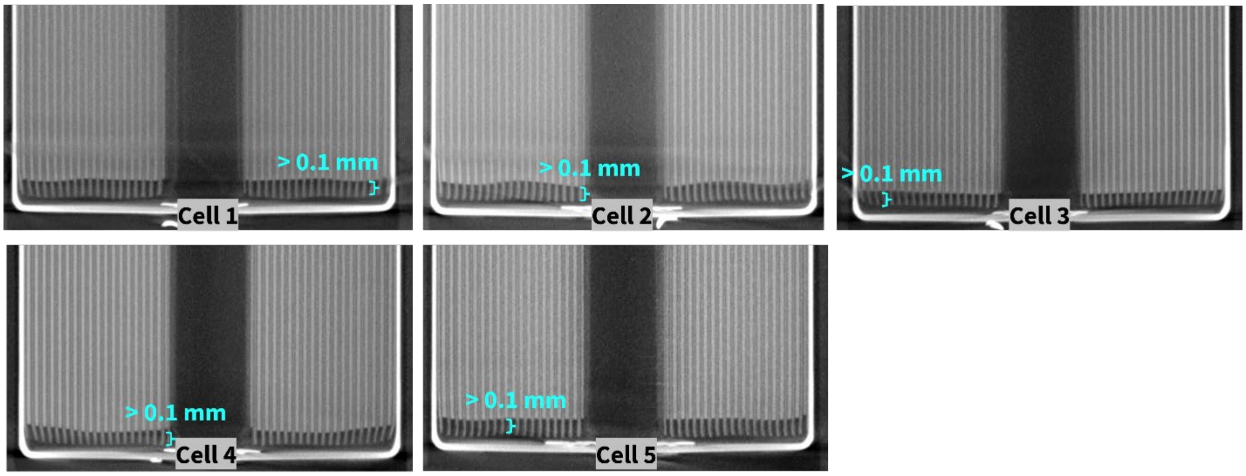


Figure B - 55. Pair 2 OEM – Pack overlap measurements. The shortest overlap region of the positive electrode by the negative electrode was measured to be above 0.1 mm industry recommendation as is recommended by IEEE 1725.

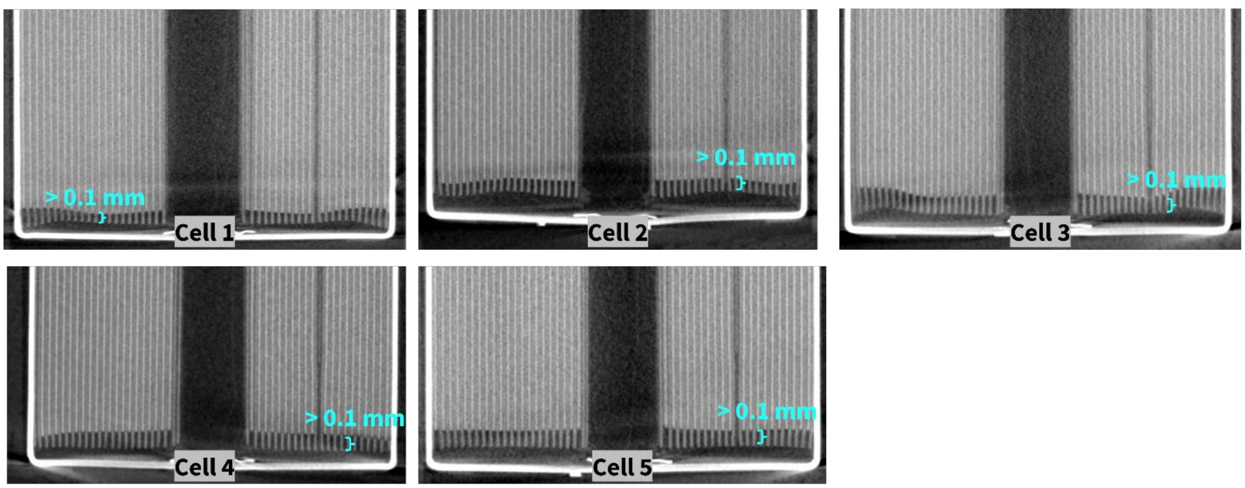


Figure B - 56. Pair 2 Rep – Pack overlap measurements. The shortest overlap region of the positive electrode by the negative electrode was measured to be above 0.1 mm industry recommendation as is recommended by IEEE 1725.

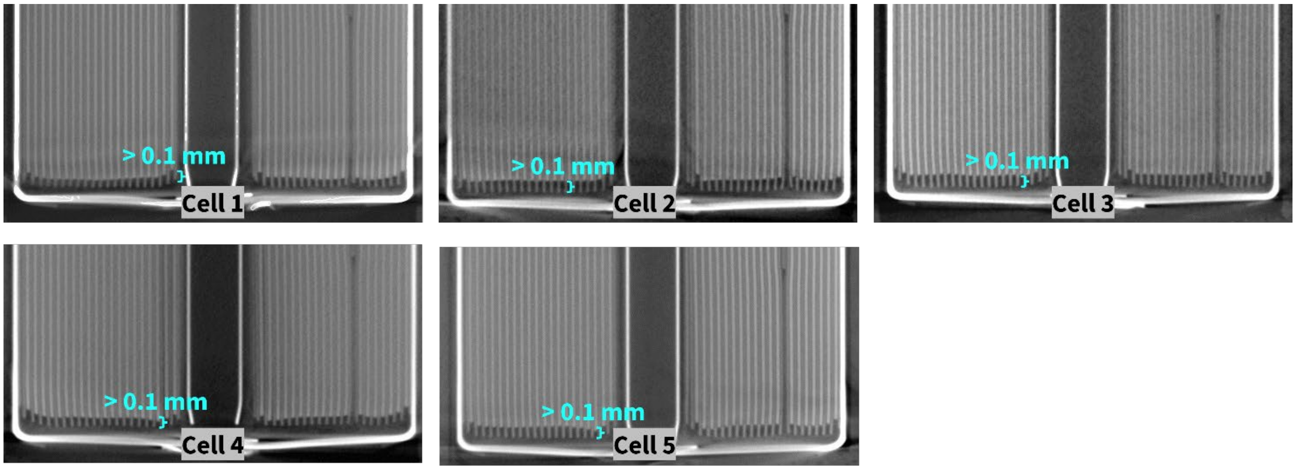


Figure B - 57. Solo – Pack overlap measurements. The shortest overlap region of the positive electrode by the negative electrode was measured to be above 0.1 mm industry recommendation as is recommended by IEEE 1725.

Appendix C

Ambient Temperature Increasing During Charging

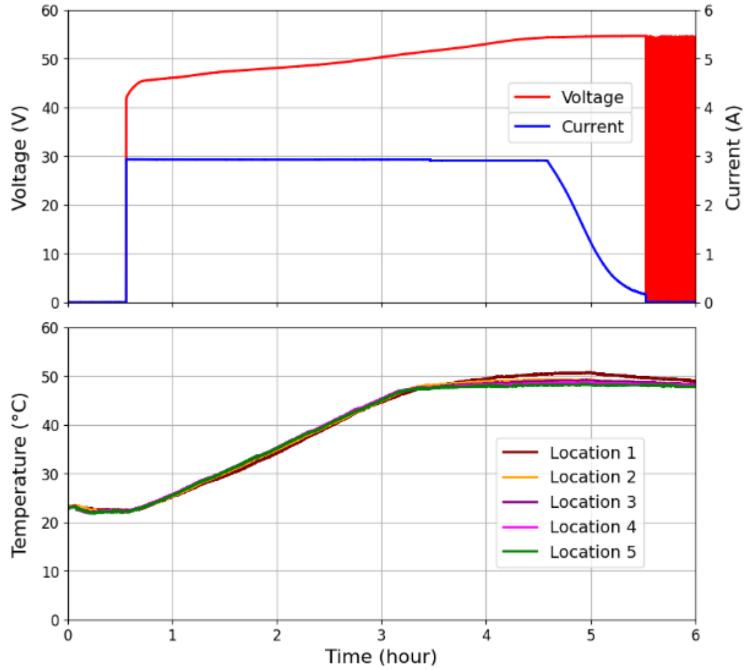


Figure C - 1. Charging of Pair 1 OEM – Pack at increasing temperature.

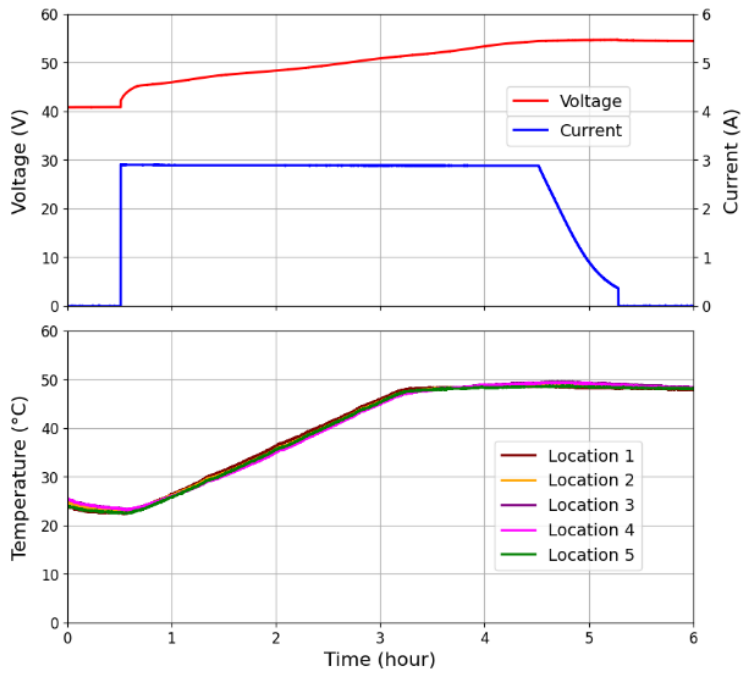


Figure C - 2. Charging of Pair 1 Rep – Pack at increasing temperature.

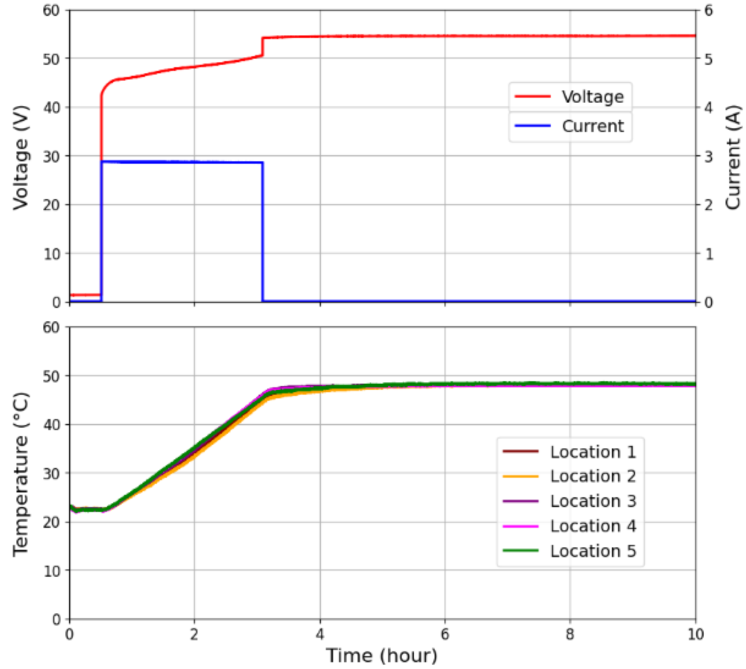


Figure C - 3. Charging of Pair 2 OEM – Pack at increasing temperature.

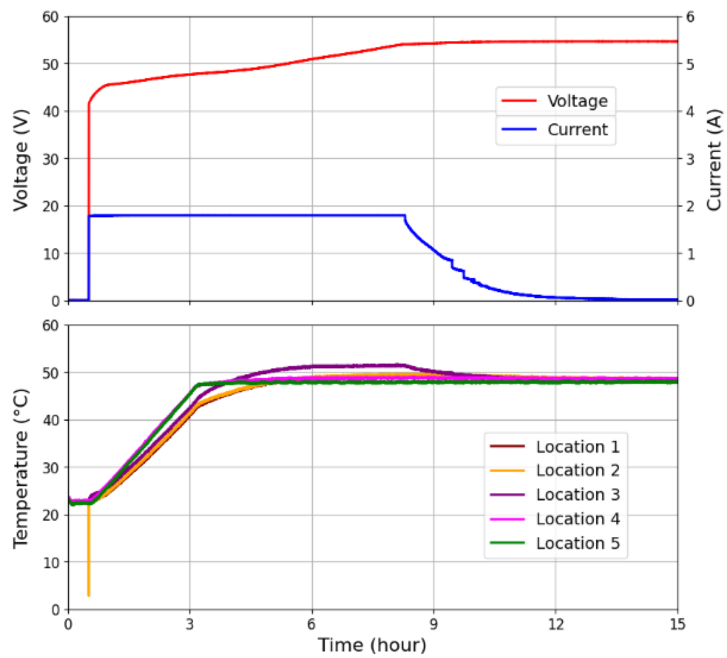


Figure C - 4. Charging of Pair 2 Rep – Pack at increasing temperature.

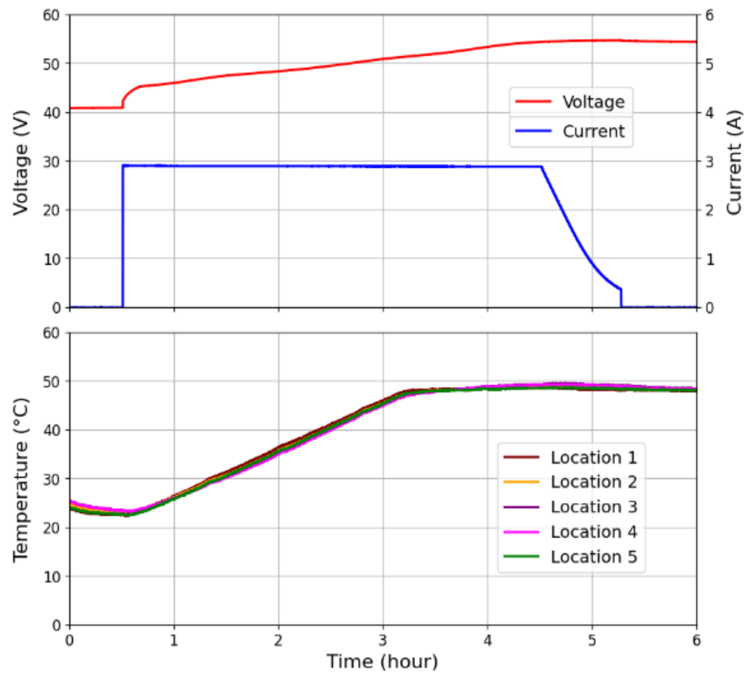


Figure C - 5. Charging of Solo – Pack at increasing temperature.

Appendix D

Ambient Temperature Decreasing During Charging

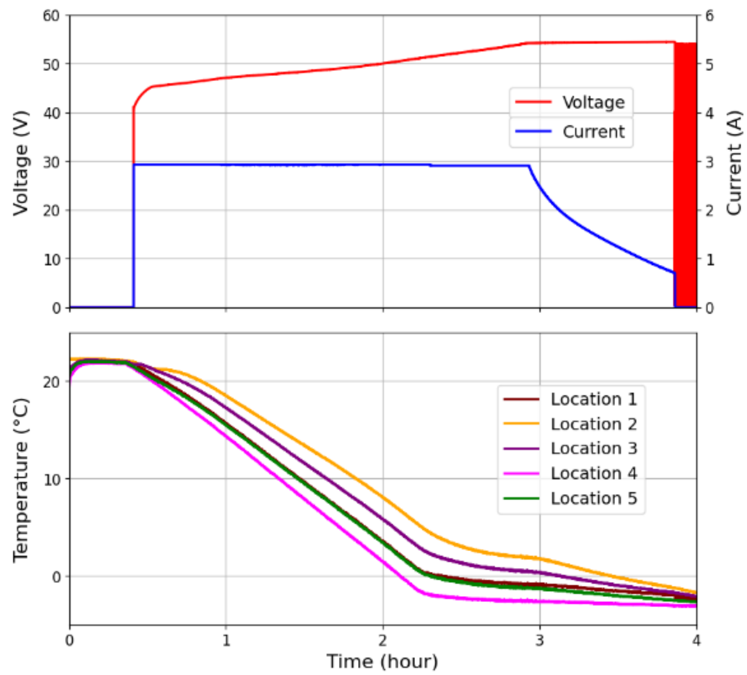


Figure D - 1. Charging of Pair 1 OEM – Pack at decreasing temperature.

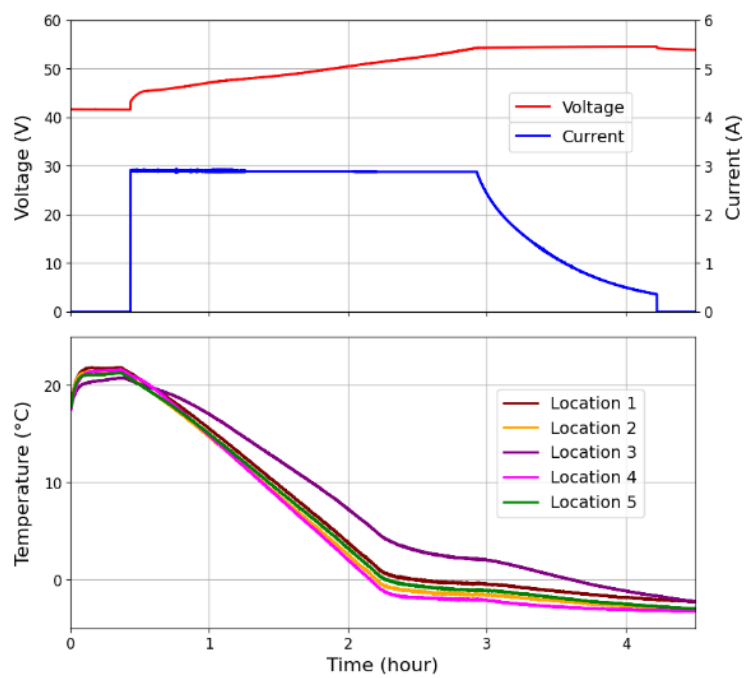


Figure D - 2. Charging of Pair 1 Rep – Pack at decreasing temperature.

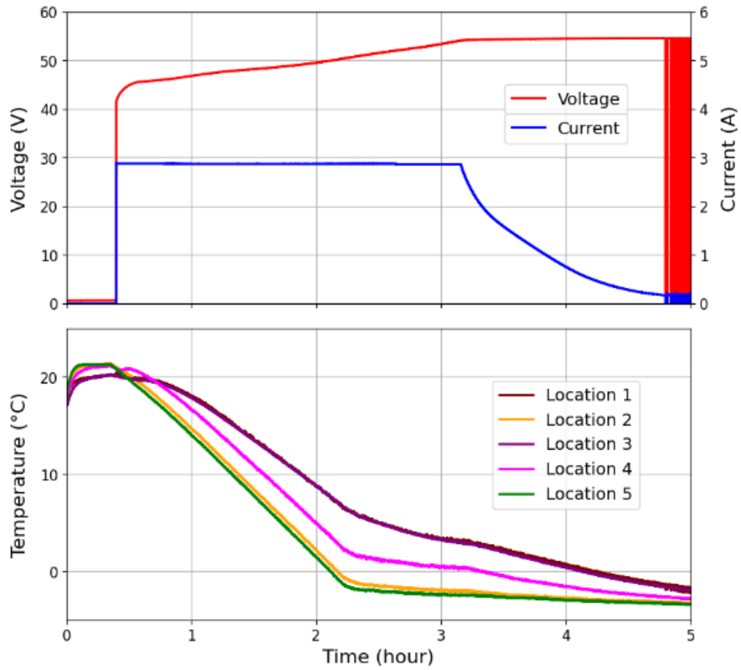


Figure D - 3. Charging of Pair 2 OEM – Pack at decreasing temperature.

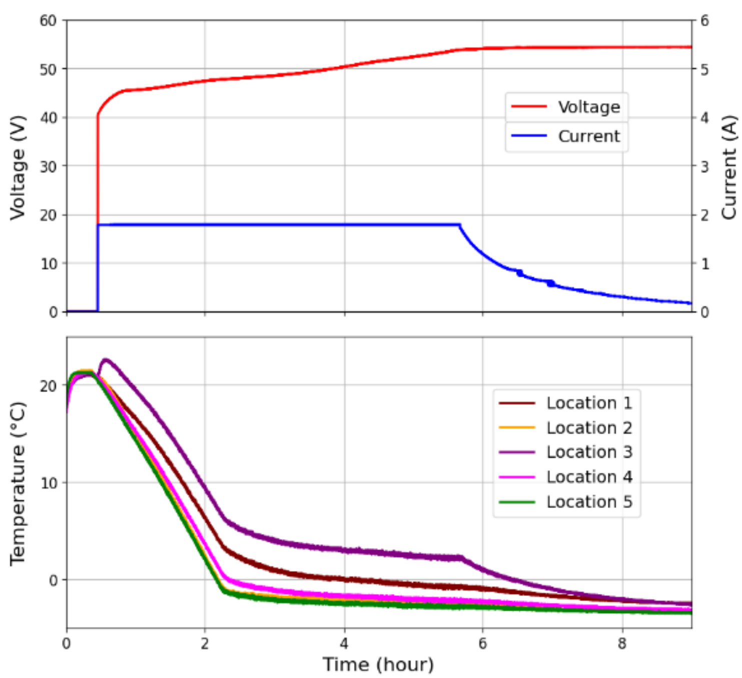


Figure D - 4. Charging of Pair 2 Rep – Pack at decreasing temperature.

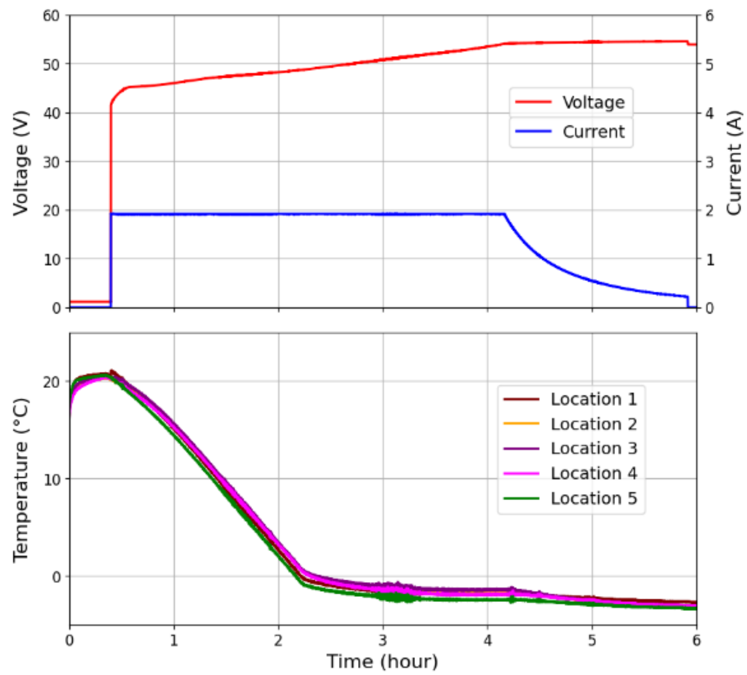


Figure D - 5. Charging of Solo – Pack at decreasing temperature.

Appendix E

Out-of-Specification Charger Current Test

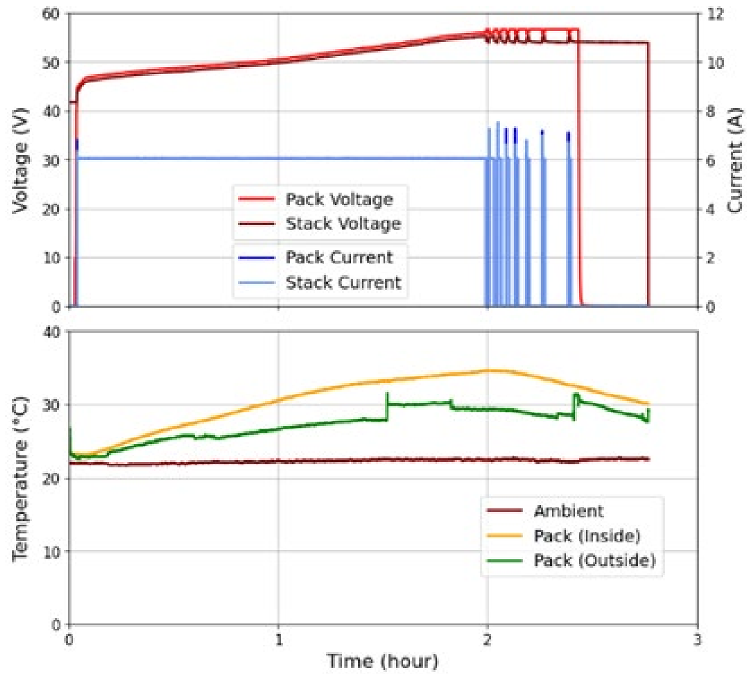


Figure E - 1. Overcharging of Pair 1 OEM – Pack (2x rated current).

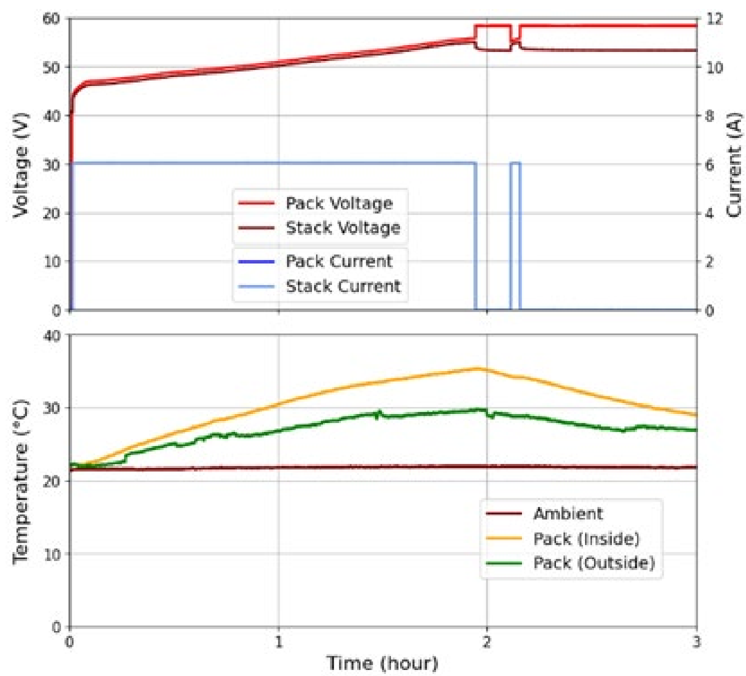


Figure E - 2. Overcharging of Pair 1 Rep – Pack (2x rated current).

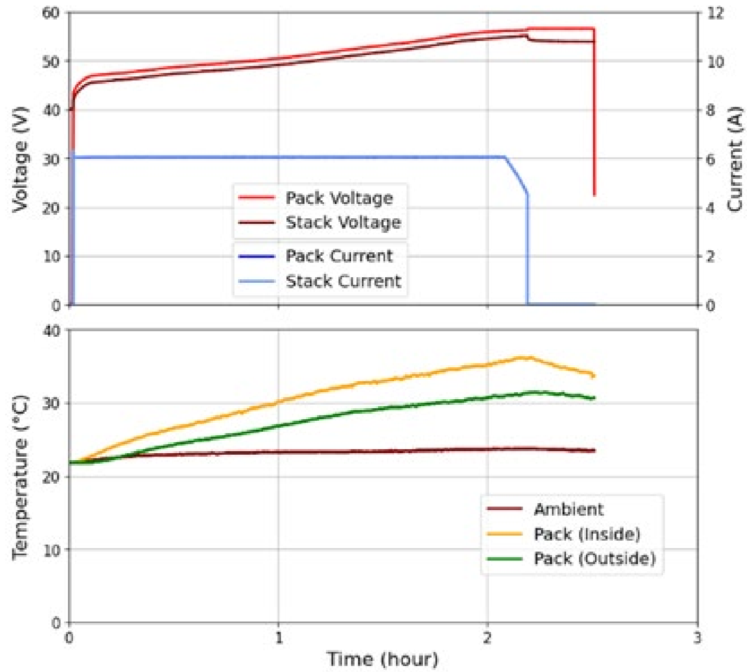


Figure E - 3. Overcharging of Pair 2 OEM – Pack (2x rated current).

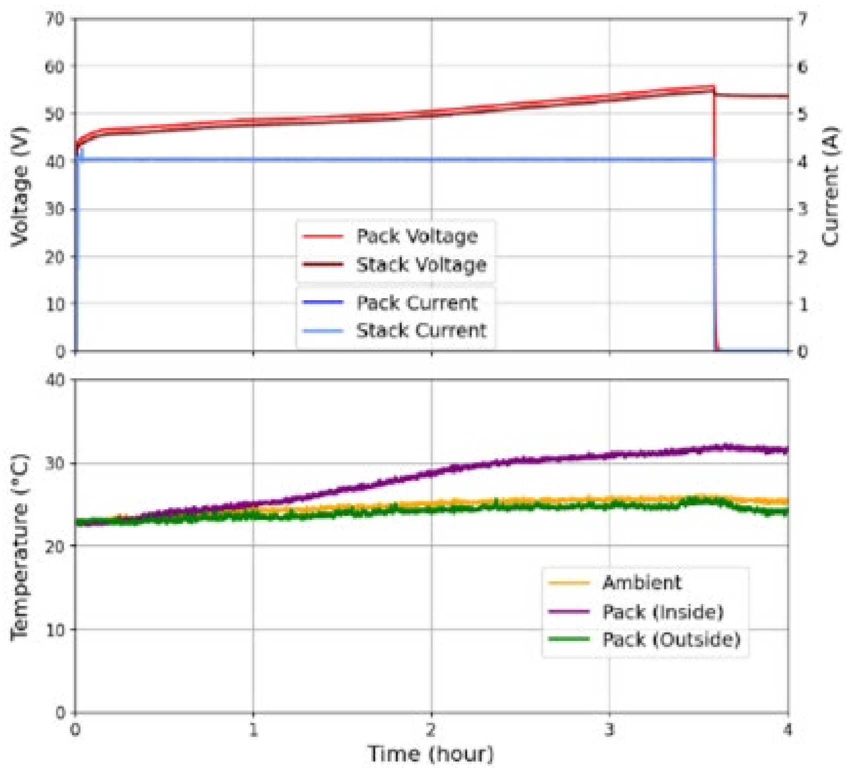


Figure E - 4. Overcharging of Pair 2 Rep – Pack (2x rated current).

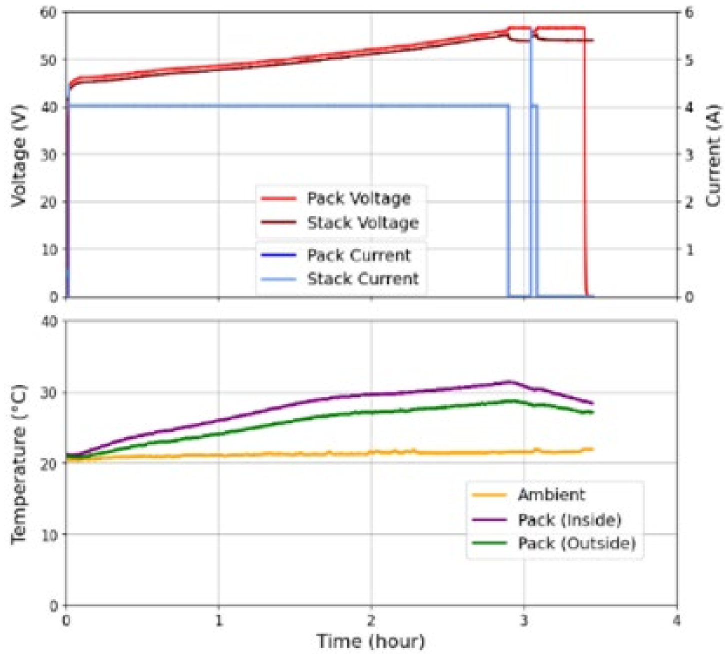


Figure E - 5. Overcharging of Solo – Pack (2x rated current).

Appendix F

Out-of-Specification Charger Voltage Test

Plots: Out-of-Specification Charger Voltage Test

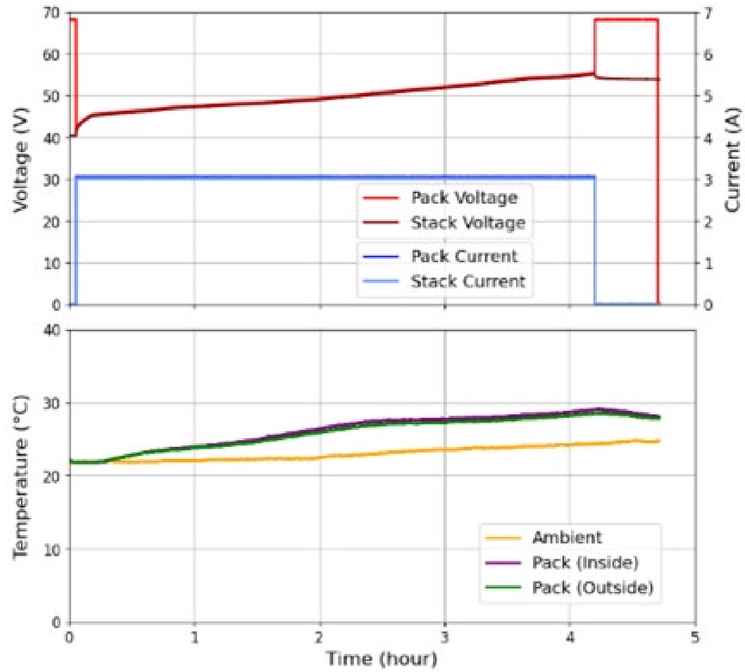


Figure F - 1. Overcharging of Pair 1 OEM – Pack (125% of rated voltage).

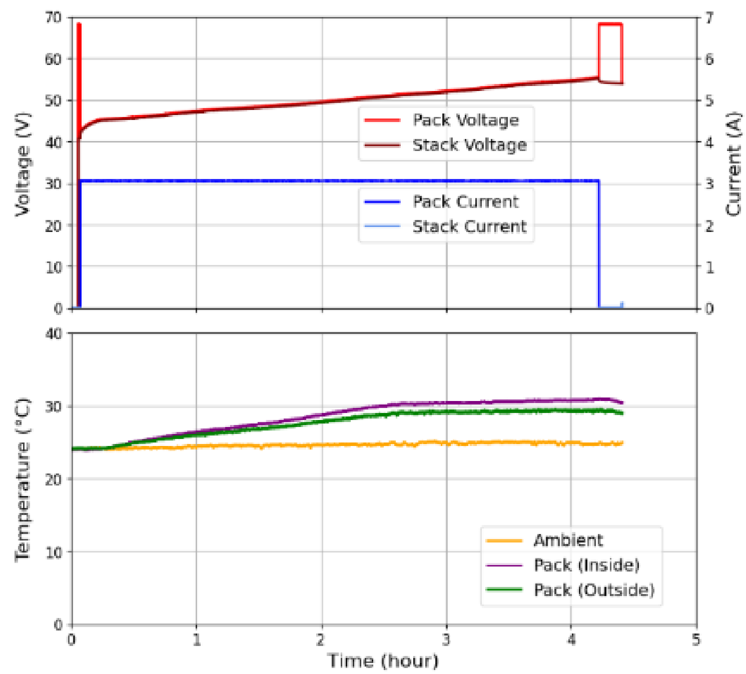


Figure F - 2. Overcharging of Pair 1 Rep – Pack (125% of rated voltage).

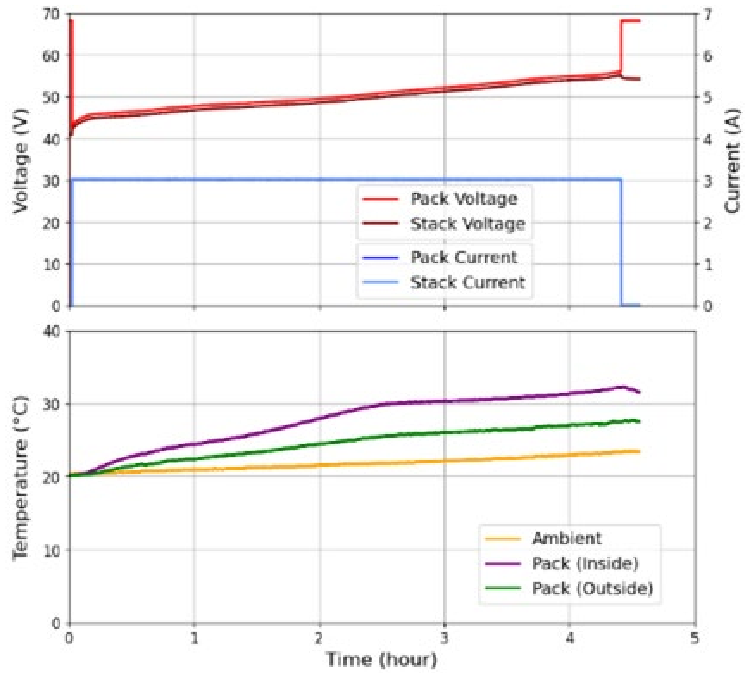


Figure F - 3. Overcharging of Pair 2 OEM – Pack (125% of rated voltage).

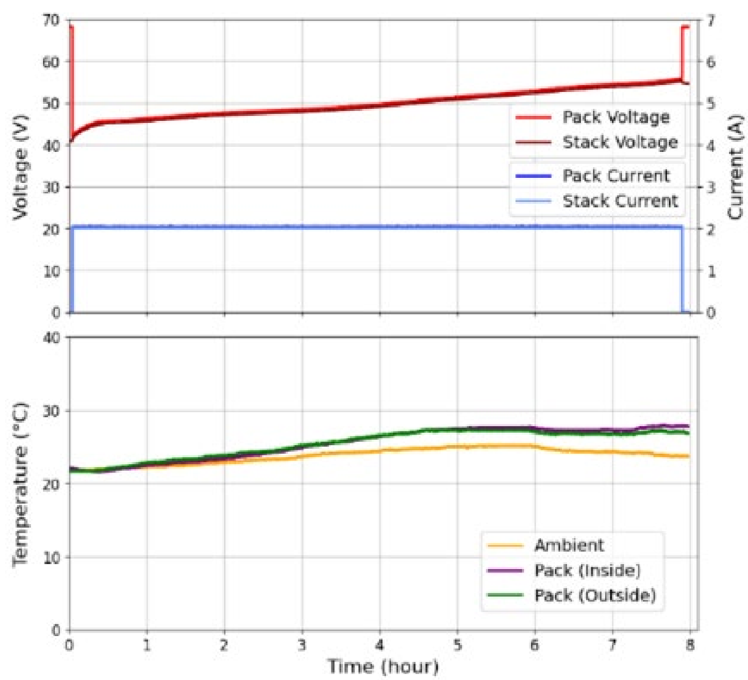


Figure F - 4. Overcharging of Pair 2 Rep – Pack (125% of rated voltage).

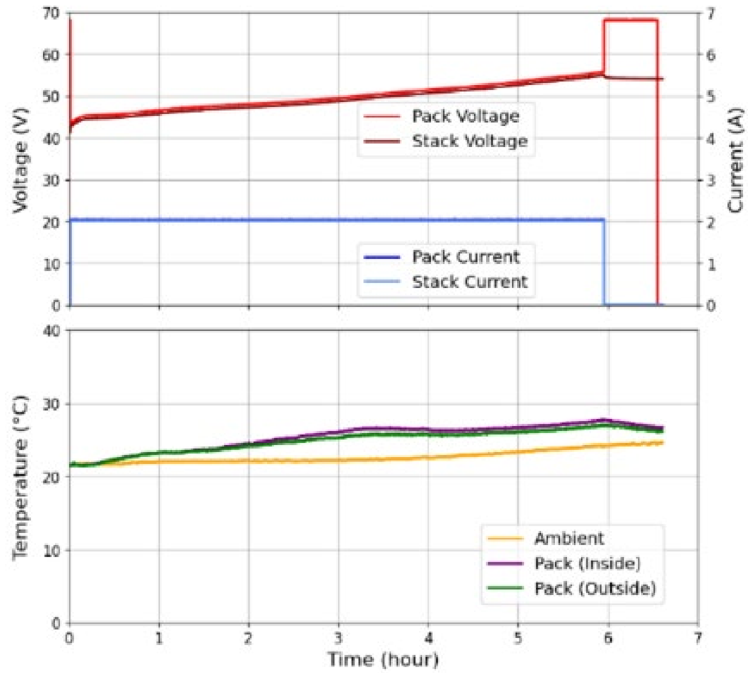


Figure F - 5. Overcharging of Solo - Pack (125% of rated voltage).

100% SOC Disassembly

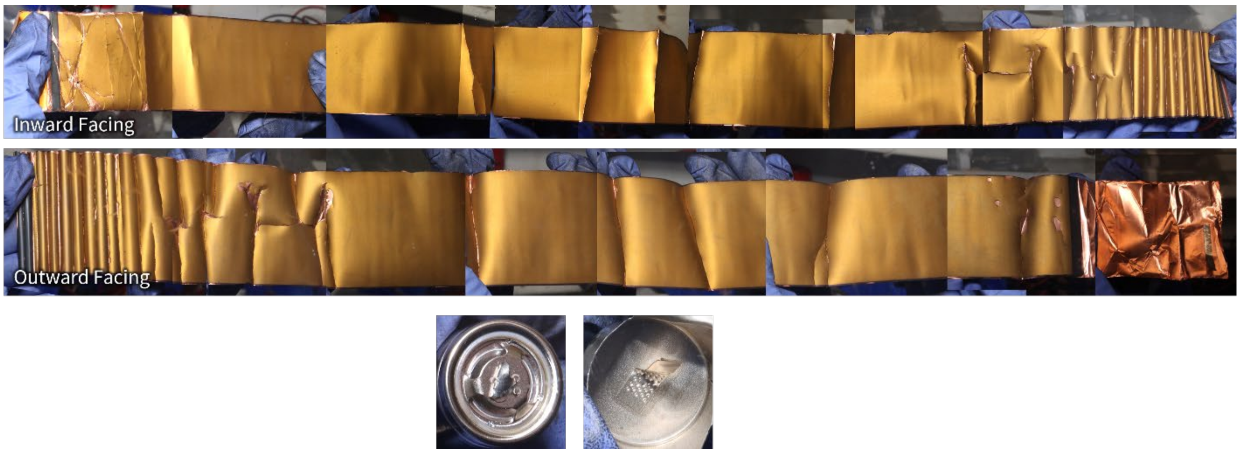


Figure F - 6. Pair 1 OEM – Pack disassembly at 100% SOC; negative electrodes are shown.

Figure F - 7. Pair 1 Rep – Pack disassembly at 100% SOC; negative electrodes are shown. A brown residue was observed on the edge of the outer can where the crimping occurs.

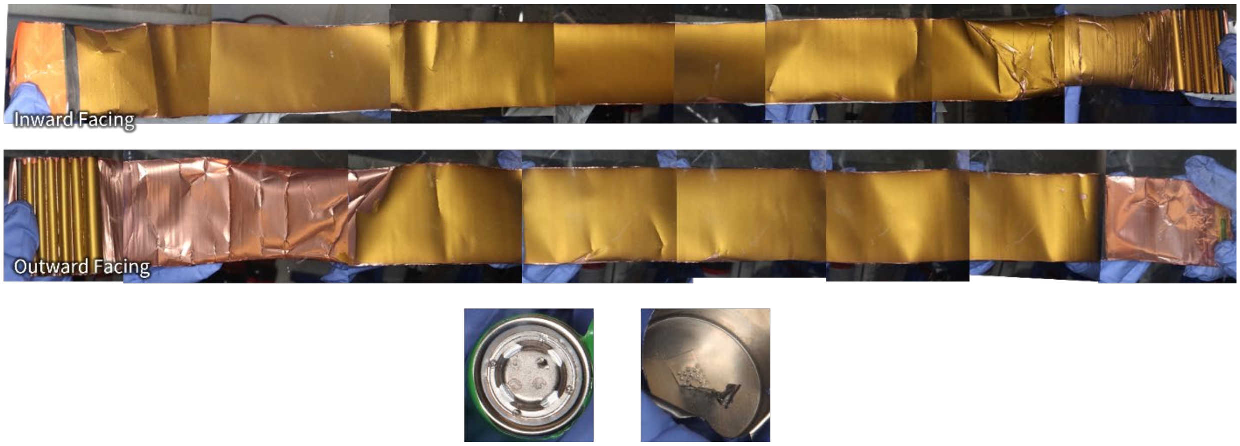


Figure F - 8. Pair 2 OEM – Pack disassembly at 100% SOC; negative electrodes are shown.

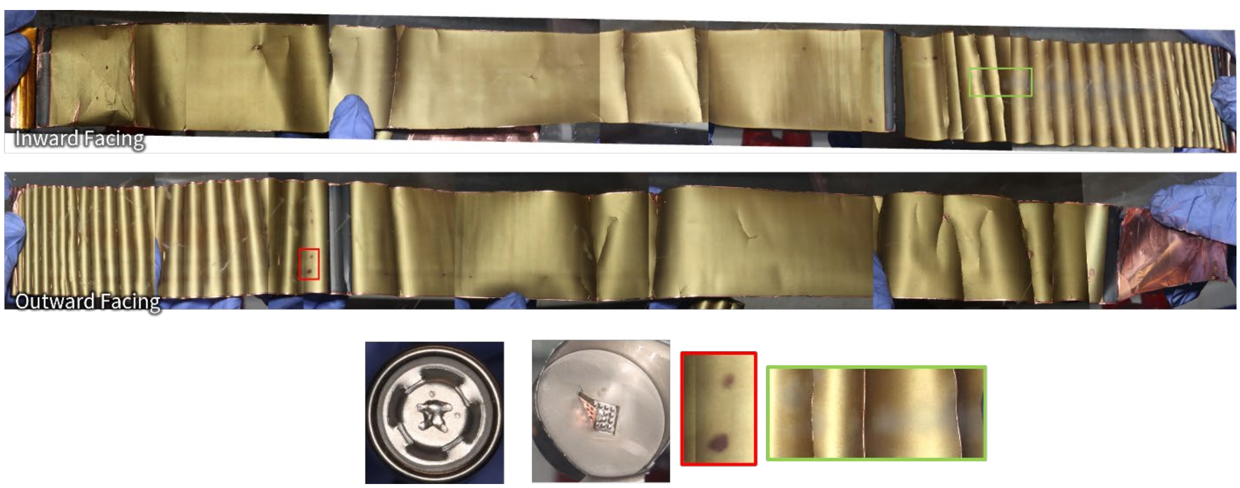


Figure F - 9. Pair 2 Rep – Pack disassembly at 100% SOC; negative electrodes are shown. Red box shows signs of underlithiation and green box shows alumina transfer from the disassembly process.

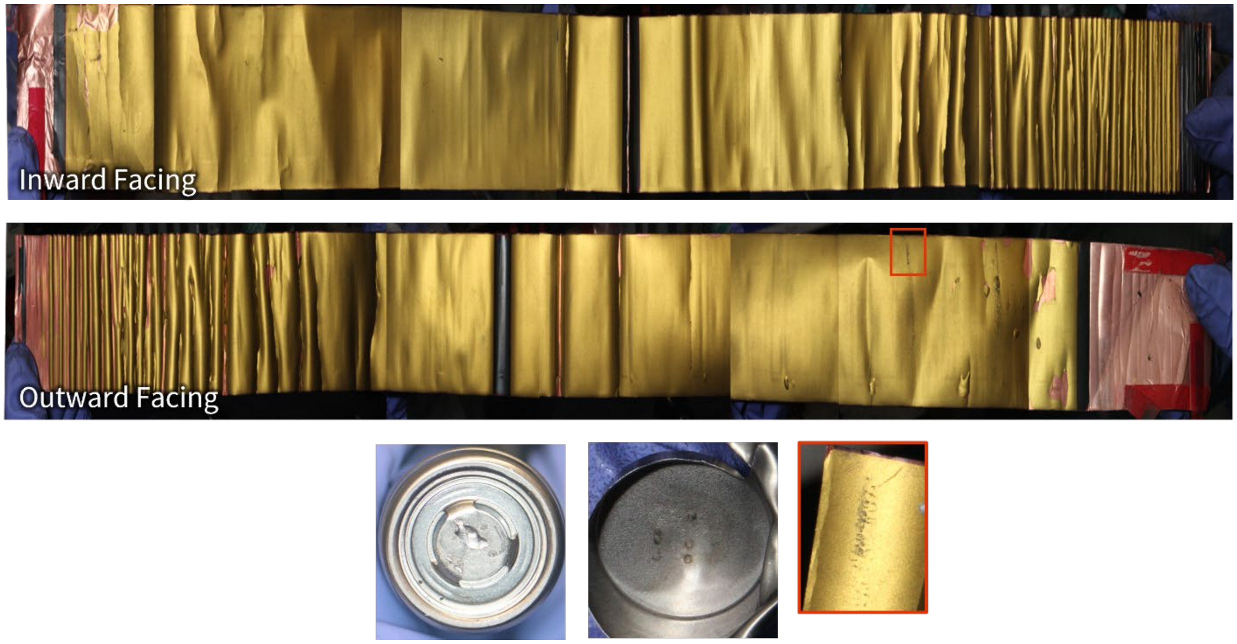


Figure F - 10. Solo – Pack disassembly at 100% SOC; negative electrodes are shown. Red box shows signs of lithium plating.