EVALUATION AND ANALYSIS OF SUBSTANDARD LITHIUM-ION BATTERIES BY UN 38.3 TESTING

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EXECUTIVE SUMMARY

Lithium-ion batteries (LiBs) are classified as a Class 9 dangerous good and when damaged, mishandled, or defective they can start a fire. Fire suppression systems in aircraft are limited in their ability to extinguish LiBs fires, making LiBs a potentially high safety hazard to aircraft and their occupants. The transportation of LiBs in Canada is regulated to minimize hazards that might occur. One criterion requires that LiBs must pass Part III of the United Nation's Recommendations on the Transport of Dangerous Goods – Manual of Tests and Criteria, Sub-Section 38.3 Tests (UN 38.3) before transport. While it can be reasonably assumed original equipment manufacturers (OEM) will manufacture LiBs that pass UN 38.3, Transport Canada wondered if lower cost third-party LiBs would be less likely to pass these tests. This study aims to find out the risk of LiBs in the transportation system failing UN 38.3, and if there are commonalities between these LiBs that will improve detection of them during transportation.

The study focused on replacement batteries for three (3) models of power tools and one (1) model of a smartphone, selected as they were found to be one of the most popular types of LiBs to be sold and shipped in volume to consumers. For each model, one (1) set of OEM LiBs and five (5) sets of third-party LiBs were procured, for a total of twenty-four sets. Each set contained at least sixteen LiBs; the minimum number of LiBs necessary for UN 38.3 testing. LiBs were procured from five (5) different online marketplaces. UN 38.3 Test Summaries were requested for each set ordered. As the packages were received in the United States, they were inspected and documented for compliance with the appropriate regulations. Underwriters Laboratories of Canada Inc. (UL) conducted both the inspection of packages and UN 38.3 testing of these batteries, under contract with Transport Canada.

Sixteen out of 24 sets had packages that were not shipped with the required markings, including packages from OEM sets. Examples of these labelling non-compliances (NCs) included mis-declaring a UN3480 package as UN3481, missing the required marking indicating the package is forbidden for transport aboard aircrafts and vessels, not including a telephone number on the UN3480 label, and not including any markings on the package indicating lithium battery products were inside the package (i.e., shipped undeclared).

All four (4) sets of OEM LiBs passed UN 38.3, while ten out of twenty sets of third-party LiBs failed UN 38.3. Seven (7) sets had NCs during vibration testing, three (3) sets had NCs during external short circuit testing, and three (3) sets had NCs during overcharge testing. Sets that failed during short circuit and overcharge testing tended to result in more severe failures, with one particular explosion during short circuit testing causing a dent in an explosion-proof test chamber.

The *Transportation of Dangerous Goods Regulations* requires LiBs shipped by air as UN3480 to have a state of charge (SOC) below 30%. A lower SOC provides an additional layer of safety during transport and reduces the likelihood of a thermal event. Of the three (3) LiB sets that seem to have been shipped by air, all were third-party LiBs and were received with a SOC above 30%, and failed UN 38.3. The combination of substandard LiBs being shipped by air and at high SOC can be especially problematic, due to increased risk by air mode if failure occurs during transport.

A detailed teardown analysis was conducted by the National Research Council of Canada (NRC) on batteries that failed UN 38.3 testing by examining them on a battery pack and individual cell level. There was nothing notable at the battery level that would increase the hazard of the battery pack, however examination at the cell level revealed that some substandard cells used in third-party batteries had significant defects that could cause severe UN 38.3 test failures.

This study reveals that third-party replacement batteries, which are usually lower cost, are more likely to be non-compliant with UN 38.3, some with severe events including fire and explosion, and thus can present a higher safety risk during transportation than their OEM counterparts. This study also reveals that there are many mislabelled, and unlabelled (undeclared) substandard LiBs being shipped, and some are being shipped by air at SOC above the 30% maximum permitted. However, the small sample size (3 of 44 packages confirmed to be shipped by air) may require further analysis to have confidence on the prevalence of substandard LiBs in the air transport system.

While no commonalities could be drawn between UN 38.3 failure and most of the factors studied (package weight, handling, marketplace, seller, courier, packaging & labelling compliance, country of origin, and mode of transportation used), these findings do point to potential correlations that could be useful for consumers, marketplaces, shippers, and inspectors to try to prevent these batteries from entering the transportation system. For example:

- A third-party LiB with higher voltage (e.g., 20V vs. 12V in this study) was more likely to fail UN 38.3 than a third-party LiB with a lower voltage.
- For sets that had severe failures during UN 38.3 tests, the substandard batteries were found to be cheaper and weighed less than their OEM counterparts, and also had typos and/or misaligned text on their labels.

By far the most likely way to avoid substandard batteries is to purchase OEM batteries. To help address the safety risks identified by this study, Transport Canada is developing strategies to increase awareness and compliance with safety requirements.

1.0 INTRODUCTION

Lithium-ion batteries (LiBs) are used as lightweight, long-lasting energy storage solutions. They can be found in many consumer electronics, from portable devices to electric vehicles. LiBs are classified as a Class 9 dangerous good, as they can pose a serious risk when being transported. LiBs that are damaged, mishandled, or defective can start a fire. These fires are especially hazardous during air transport, as extinguishing these LiBs fires in-flight can be very difficult.

High volumes of LiBs are being shipped each year, and that volume is increasing. Among these shipments are common consumer product replacement LiBs that may be shipped by air to reach consumers quickly. To minimize hazards that might occur during transportation by all modes, including air, the transportation of LiBs in Canada is regulated under the *Transportation of Dangerous Goods Regulations* (TDGR). The TDGR requires that LiBs must pass the tests set out in subsection 38.3 of Part III of the UN Manual of Tests and Criteria (UN 38.3) prior to transport.

Substandard LiBs – defined in this study as LiBs that do not pass the UN 38.3 Testing – are a growing concern, in part because of the increasing number of these substandard LiBs emerging in online marketplaces and the transportation system. While it can be reasonably assumed that reputable manufacturers will manufacture LiBs that uphold UN 38.3 test requirements, substandard batteries manufactured by third parties may not. An investigation conducted by the United States Pipeline and Hazardous Materials Safety Administration (PHMSA) raised concerns with shippers being unable to provide valid test reports as required under UN 38.3 [1]. Portable Rechargeable Battery Association has also suggested many of the worst abuses of substandard batteries originate in China [2].

The Transportation of Dangerous Goods (TDG) Program, as part of the Safety and Security Group at Transport Canada serves as the major source of regulatory development, information, and guidance on dangerous goods transport for the public, industry, and government employees. To prioritize the safe transport of LiBs in the transportation system, the TDG's Safety Research and Analysis – Scientific Research Team (SR) conducted this study to assess the performance of third-party replacement LiBs against UN 38.3 to see how they compare to their Original Equipment Manufacturer (OEM) LiB counterparts. Through an earlier initial research study, SR found that a small sample of common consumer LiBs failed UN 38.3 testing, outlining a potential risk that TDG decided to study further.

In this study, the scope is expanded to include a larger sample size of LiBs. By assessing the prevalence of substandard LiBs in transport, where they come from, how they are transported, and what types and severity of non-compliances (NC) are found, SR aimed to assess the risk substandard LiBs pose in the air transport system. Additional analysis was done on substandard LiBs at the battery and individual cell level, to understand reasons as to why the batteries in this study failed UN 38.3 testing and if they increased risk compared to LiBs that passed this testing. This study also aimed to identify factors or indicators that might help identify suspect LiBs and packages for UN 38.3 non-compliances, to help consumers, marketplaces, shippers, and regulators mitigate or prevent these batteries from entering the transportation system.

1.1 Previous Research Study

SR performed prior research into LiBs meeting the UN 38.3 Test standard from 2016 to 2017. A small sample of three types of battery packs (a power bank, a battery assembly, and a battery used for vaping devices) was tested in two separate laboratories. The two laboratories independently conducted UN 38.3 Testing, 6th edition [3]. More details for each of the tests are found later in Section 2.3 UN 38.3 Testing of Batteries.

Table 1: Previous Study UN38.3 Test Results

Battery Type	**Laboratory 1**		**Laboratory 2**	
	x1 cycled batteries	*x50 cycled batteries*	*x1 cycled batteries*	*x50 cycled batteries*
Battery Type 1	Failure at T2	Pass	Pass	Pass
Battery Type 2	Failure at T2	Failure at cycling	Failure at T2	Failure at T2
Battery Type 3	Failure at T4	Failure at cycling	N/A	N/A

All batteries procured failed the UN 38.3 test from at least one laboratory [Table 1]. This showed that there was a possibility that lithium batteries are being shipped that could also have failed the UN 38.3 test requirements. However, since only three types of batteries were selected and a large variance in results made it difficult to extract any concrete conclusions, several recommendations were made for future work in this area:

- Test an extended sample collection of batteries, including reputable manufacturers as a baseline measurement.
- Add testing of the cells to the testing of the batteries to get a better understanding of the cells and batteries behavior and compliance.
- Enable traceability of products and components, to identify how many batteries failed and how they failed.
- Perform a destructive physical analysis for each sample that fails, to investigate and document failure (as it could be related to design, assembly, mechanical stress, manufacturing)
- Document shipping and packaging aspects of the batteries, to understand the abuse conditions of batteries before testing as well as determining a shipper's compliance to UN 38.3 Testing.

These recommendations were further refined to form the purpose and testing methodology of this study.

1.2 Current Research Study

The goal for this project is to understand the hazards and risks posed by commonly transported LiBs during shipping by air. The criteria to establish which LiBs would be considered a risk would be the LiB type's prevalence in the consumer marketplace and its ability to pass the UN 38.3 testing requirements. The method for incentivizing shippers to send packages by air is described in 2.1 Selecting Mode of Transportation, however it should be noted that despite these efforts, most LiBs being tested in this study can only be confirmed to have been shipped by ground.

The study also aims to inform on how suppliers are shipping LiBs and if the packaging and labelling follows regulations. The objective is to identify any commonalities between substandard LiBs that will improve detection of them during transportation.

2.0 METHODOLOGY

The first step in the project was to select the types of batteries that would undergo UN 38.3 Testing. Following this, a method to document shipping and package details needed to be established in consultation with Transport Canada TDG inspectors. Finally, it was necessary to have an ISO 17025 or ISO 9001 certified laboratory that could perform UN 38.3 testing. A selection of batteries that failed UN 38.3 testing were sent to the National Research Council Canada for additional teardown analysis of the battery pack and individual cells, to see if any conclusions could be drawn on why these batteries failed.

2.1 Procurement of Batteries

The batteries to be tested in this study were selected based on which batteries had the highest volume purchased by consumers on common online marketplaces. It was assumed that large companies shipping or receiving LiBs, such as those for electric vehicles, would be able to verify that all parts of their supply chain involved with these LiBs are complying with the TDGR. However, consumers and smaller businesses may be less aware of the regulations when shipping or receiving batteries. This rationale provided a set of logical steps to take to determine what LiBs to purchase for this study.

Top Canadian Marketplaces

Both physical and digital marketplaces sell LiBs, and physical locations typically have an online website as well. A review of the top Canadian marketplaces in 2020 by online site visits [4], as well as global marketplaces with an online English storefront [5], was completed to determine sites for sourcing batteries for this study.

Top LiBs by volume per marketplace

After selecting the marketplaces, each marketplace was searched to determine what the most common category of “lithium-ion battery” are available. Each marketplace determines the ranking of the products in a different manner and tend to hide exact sales figures, instead using labels like *best-selling* or *popular* on the product page.

In addition to marketplace searches, a general search was performed on the most popular consumer electronics and battery incident data from the USA Federal Aviation Administration (FAA) [6].

Table 2: Ranking of most popular LiB products across three marketplaces by estimated sales

Rank	Item (Market A)	Item (Market B)	Item (Market C)	Popular Consumer Electronics	FAA reports
1	Ear/headphones	Smartphones	Smartphones	Ear/Headphones	e-cigarettes
2	Portable speaker	Power tools	Tablets	Portable speakers	Laptops
3	Microphone / Loudspeaker	Ebikes/scooter	Power tools	Portable radios	DVD player
4	Smartphones	Solar chargers	Power banks	Solar chargers	Smart Meter
5	Power tools		Heated gloves		GoPro
6	Smartwatches		Cameras		Welding Device
7	Portable Consoles				Portable Speaker
8	Game Controllers				Cellphone

Selection of LiB Type

Base cell form factors such as the 18650 cells were not chosen as the direct application of these cells is not commonly purchased as just a replacement cell by consumers to the items in Table 2. From the rankings in Table 2, power tool batteries are sold in significant quantities across all researched marketplaces and are easily replaceable by the consumer. Of interest is that third-party replacement LiBs are also sold at considerably lower prices than the Original Equipment Manufacturer (OEM) LiBs, suggesting that compromises may have been made to produce those third-party batteries. In general, power tool batteries have high wattage and therefore energy, which can lead to more severe failure events in transportation [7]. With all these considerations, the main type of LiB this study focused on was replacement power tool batteries.

A different type of battery was also selected as an exploration of the LiB market outside of power tools. Replaceable smartphone batteries make up the majority of purchased LiBs across all the marketplaces in Table 2. Current smartphone batteries are typically soldered and hardwired to the phones circuit board, so it was assumed that the average consumer would not be purchasing this type of LiB, as they would need to solder high precision electrical components together. However, the data suggests that that many people are purchasing these replaceable batteries nonetheless and they are being shipped at high volume, indicating that this is another market to consider. Thus, smartphone batteries were chosen as an exploratory study.

Selection of LiB Models

Three models of power tool batteries were selected for testing based on most popular ranking across all three online marketplaces. A separate website was used to verify the brands have high market share among all tool brands [8]. An additional criterion was to pick only one model from each brand and to have different wattage ratings between all three models. The range of voltage selected was from 12V to 20V, and a capacity from 1.5Ah to 7Ah. A similar method was used to select the exploratory smartphone LiB.

Selection of LiB Sets

With the type of battery and models from OEM selected, a matrix to build out a list of LiB sets was developed. For the purposes of this study a set is defined as twenty-five identical single battery units. Each letter refers to specific model of the OEM battery as follows:

(A) Sets A1, A2, A3, A4, A5, and A6 are intended to be a Model A replaceable power tool battery
(B) Sets B1, B2, B3, B4, B5, and B6 are intended to be a Model B replaceable power tool battery
(C) Sets C1, C2, C3, C4, C5, and C6 are intended to be a Model C replaceable power tool battery
(D) Sets D1, D2, D3, D4, D5, and D6 are intended to be a Model D replaceable smartphone battery

OEM batteries are assigned the number 1. Third-party replacement battery sets are numbered 2, 3, 4, 5, and 6.

For selecting replacements, product descriptions were reviewed for a reasonable suspicion of being substandard, by drawing from a brainstormed list of identifiers listed below. Additionally, replacement batteries were selected by volume sold, resembling what a consumer would purchase without sorting through all available products. Rationales include:

- Cost – LiBs listed lower than the cost of the OEM LiBs,
- Marketplace Review – LiBs listed as being sponsored, best-selling, or highly-rated by previous purchasers,
    - Advertising – LiBs listed with a higher capacity or voltage than the OEM LiBs
    - Shipping – LiBs listed with express or free shipping,
    - Certification – “Certified” markings, or a seller name containing numbers, underscores, and other non-traditional symbols

Along with the four OEM models, twenty other replacement battery LiBs from third parties were selected for a total of twenty-four sets to be tested. Table 3 includes the list of sets procured, their individual cost per unit and rational for selection:

Table 3: LiB Sets Selected for Study

Set ID	Marketplace	Cost (USD/unit)	Advertised Power	Reason for selection
A1	Market A (linked by OEM store)	$118.00	120Wh 20V/6.0Ah	Original OEM model
A2	Market B	$24.00	120Wh 20V/6.0Ah	“Sponsored” item as listed on Market B
A3	Market A	$24.00	120Wh 20V/6.0Ah	Lowest cost on storefront
A4	Market C	$22.61	200Wh 20V/10.0Ah	Advertised a higher capacity than the OEM LiB (10Ah instead of 6Ah)
A5	Market A	$29.50	120Wh 20V/6.0Ah	Brand name matches closely with another battery brand (B3)
A6	Market B	$24.00	120Wh 20V/6.0Ah	Highly rated battery
B1	Market D (linked by OEM store)	$105.19	72Wh 12V/6.0Ah	Original OEM model
B2	Market B	$19.00	72Wh 12V/6.0Ah	Confirmed Expedited Shipment
B3	Market A	$23.95	72Wh 12V/6.0Ah	Market A’s Choice for battery
B4	Market B	$15.10	72Wh 12V/6.0Ah	Lowest cost model on storefront
B5	Market A	$19.50	72Wh 12V/6.0Ah	Lowest cost model on storefront
B6	Market C	$24.26	72Wh 12V/6.0Ah	“Popular” as listed by Market C
C1	Market A (linked by OEM store)	$62.45	60Wh 20V/3Ah	Original OEM model
C2	Market A	$17.99	60Wh 20V/3Ah	Lowest cost on storefront
C3	Market B	$18.50	30Wh 20V/1.5Ah	Lowest cost on storefront
C4	Market B	$28.88	140Wh 20V/7Ah	Expedited Shipment
C5	Market B	$21.99	80Wh 20V/4Ah	Comparison to 3Ah version
C6	Market C	$48.29	60Wh 20V/3Ah	Expedited Shipment
D1	Market E (linked by OEM store)	$39.99	12.32Wh 3.85V/3.2Ah	Original OEM model
D2	Market A	$13.99	17.017Wh 3.85V/4.42Ah	Advertised a higher capacity
D3	Market B	$8.31	14.08Wh 4.40V/3.2Ah	Expedited Shipment
D4	Market B	$7.99	12.32Wh 3.85V/3.2Ah	Lowest cost model on storefront
D5	Market C	$3.28	12.32Wh 3.85V/3.2Ah	Lowest cost model on storefront
D6	Market C	$15.39	15.785Wh 3.85V/4.1Ah	Most Ordered

Selecting Mode of Transportation

Though the primary concern for LiB transport risk is during air cargo shipment, it was not possible to directly control how a seller would ship the batteries for this project. Some LiB were selected specifically if they mentioned air shipment or had an expedited shipping option that allowed the package to arrive in the fastest shipping option available. Knowing the timeframe between when a package had left a facility and when it was received would help determine whether air or ground shipment was used. Another method of verifying the mode of transportation involved reading the package labels indicating air or ground shipment.

2.2 Documenting Shipping and Packaging of LiB

As a secondary goal, the study aimed to determine how suppliers are transporting LiBs and if the packages are compliant with transportation regulations. The study documented a package’s compliance under three categories outlined in the ICAO Technical Instructions for the Safe Transportation of Dangerous Goods by Air [9]:

- The supplier can supply a UN 38.3 Test Summary
- The shipment is packaged and labelled correctly
- The batteries inside the package do not exceed 30% State of Charge (SOC)

While damage to a package during shipment does not make a shipment or package non-compliant, it may influence UN 38.3 Testing results. Therefore, documenting package handling conditions upon receipt is also important. From a previous study [10], different package weights affect what the LiB experiences in shipping, which could play a factor in how the LiB performs in post-shipment UN 38.3 testing. As a result, LiBs ordered would be divided into a small order, where the number of LiBs purchased will have a gross weight of less than 5kg, and a large order where the number of LiBs purchased will have a gross weight greater than 5kg.

For the D sets, only one order was placed for each set, as the combined weight of all the smartphone batteries would not exceed 5kg.

Inspection Checklist for Packages

An inspection checklist was developed with the assistance of Transport Canada TDG Inspectors. This checklist was provided to our contractor's shipping/receiving personnel to ensure the package state and compliance was well documented upon receipt. In the study, the packages were shipped to the US and so references to the TDGR was replaced with similar sections of the 49 CFR. Multiple photographs of the outer package, internal packaging, and the battery itself were taken in addition to the checklist.

Table 4: Inspection Checklist

	Item	
1.	What is the weight of the whole package	kg
2.	What are the dimensions of the outer package (L x W x H)	cm
3.	Name of carrier company	
4.	Is the labelling of the outer package correct according to the d?	Yes/No
5.	Is the shipping document correct according to the TDGR?	Yes/No
6.	Is the outer package damaged?	Yes/No
7.	Is the outer packaging appropriate according to the TDGR?	Yes/No
8.	Do the Batteries have sufficient protection within the outer package according to the packaging instructions?	Yes/No
9.	How many Batteries were contained in the outer package	
10.	What is the weight of an individual Battery	g
11.	Do the Batteries show any signs of deformation, physical damage, dents, apparent breakage, leakage, default or other abnormalities?	Yes/No
12.	Was the UN38.3 test result summary provided by manufacturer?	Yes/No
13.	Are there any other issues with the packaging? (explain below)	Yes/No

State of Charge (SOC)

There are different methods for calculating the SOC of a LiB. In this study, the SOC was determined by first charging the battery from the SOC as shipped to full capacity to get the initial measured charge capacity. Then the LiB is completely discharged, and recharged to full, which determines the full charge capacity. The SOC is then represented as such:

$$State\ of\ Charge\ (SOC) = \left(1 - \frac{initial\ measured\ charge\ capacity}{full\ charge\ capacity}\right) x\ 100\%$$

Equation 1: Equation for State of Charge

The SOC requirement is only applicable to battery shipments sent by air, and so this non-compliance was only assessed for those packages suspected of having been shipped by air which were A4, B2, and C6 (shown later in Table 6 in section 3.1).

2.3 UN 38.3 Testing of Batteries

UN 38.3 Testing was performed according to the UN Manual Tests and Criteria, 7th edition [11]. Testing includes eight different tests labelled T.1 to T.8. For power tool LiBs, T.6 (Impact/Crush) and T.8 (Forced Discharge) tests are not required according to the manual because those tests only apply to cells, not batteries made up of multiple cells. To perform the tests, 16 LiBs from each set are required, eight (8) cycled once and eight (8) cycled 25 times. Tests T.1 to T.5 shall be conducted in sequence on the same battery using four (4) single-cycled LiB and four (4) 25-cycled LiB. Test T.7 is conducted on the LiBs that were not used for tests T.1 through T.5.

Typically, once a LiB has had any test failure no further testing is conducted (i.e., T.2 - T.5 would not be done if one or more of the eight (8) batteries failed T.1). As this testing was for research purposes, testing was completed in its entirety, if possible, with individual non-compliant batteries removed from further testing after each test.

Charge Discharge Cycling

Prior to performing the tests, the samples are charge/discharge cycled either 1 time or 25 times, depending on the specific test requirement, with the LiB placed in an explosion proof enclosure during the duration of the cycle. The discharge rates depended on the set according to specification information of the OEM model:

- Model A battery sets had a 4A discharge rate applied.
- Model B battery sets had a 10A discharge rate applied.
- Model C battery sets had a 3A discharge rate applied.
- Model D battery sets had a 640mA discharge rate applied.

UN 38.3 Tests

Table 5 describes the purpose of each of the tests that were applied on the LiBs for this study, along with the procedure and requirements necessary for passing each test. More information on the UN 38.3 Test is available on the UNECE website [3].

Table 5: Description of UN 38.3 Tests specific to the project T1-T5, T7 [11]

Test	Description	Procedure	Pass requirements
T1 – Altitude simulation	This test simulates air transport under low-pressure conditions	Test cells and batteries shall be stored at a pressure of 11.6 kPa or less for at least six hours at ambient temperature (20 ± 5°C) (section 38.3.4.1.2).	Cells and batteries meet this requirement if there is no leakage, no venting, no disassembly, no rupture, no fire and if the open circuit voltage of each test cell or battery after testing is not less than 90% of its voltage immediately prior to this procedure (section 38.3.4.1.3).
T2 – Thermal test	This test assesses cell and battery seal integrity and internal electrical connections. The test is conducted using rapid and extreme temperature changes.	Test cells and batteries are to be stored for at least 6h at test temperature equal to 72 ± 2 °C, followed by storage for at least 6h at a test temperature of -40 ± 2 °C . The max time interval between test temperature extremes is 30 min. This procedure is to be repeated until 10 total cycles are complete, after which all test cells and batteries are to be stored for 24h at ambient temperature (20 ± 5°C). For large cells and batteries, the duration of exposure to the test temperature extremes should be at least 12 h (section 38.3.4.2.2).	Cells and batteries meet this requirement if there is no leakage, no venting, no disassembly, no rupture, and no fire and if the open circuit voltage of each test cell or battery after testing is not less than 90% of its voltage immediately prior to this procedure. The requirement relating to voltage is not applicable to test cells and batteries at fully discharged states (section 38.3.4.2.3).
T3 - Vibration	This test simulates vibration during transport.	Cells and batteries are firmly secured to the platform of the vibration machine without distorting the cells as to faithfully transmit the vibration. The vibration shall be sinusoidal waveform with a log sweep between 7 Hz -200 Hz and back to 7 Hz traversed in 15 min. The cycle shall be repeated 12 times for a total of 3 h for each of 3 mutually perpendicular mounting positions of the cell. One of the directions of vibration must be perpendicular to the terminal face. The log frequency sweep shall differ for cells and batteries with a gross mass of not more than 12 kg (cells-small batteries) and for batteries with a gross mass > 12 kg (large).For cells and small batteries: from 7 Hz a peak acceleration of 1gn is maintained until 18 Hz is reached. The amplitude is then maintained at 0.8 mm (1.6 mm total excursion) and the frequency increased until a peak acceleration of 8gil occurs (approximately 50 Hz). A peak acceleration of 8gn is then maintained until the frequency is increased to 200 Hz (section 38.3.4.3.2)	Cells and batteries meet this requirement if there is no leakage, no venting, no disassembly, no rupture, no fire during the test and after the test and if the open circuit voltage of each test cell or battery directly after testing in its third perpendicular mounting position is not less than 90% of its voltage immediately prior to this procedure. The requirement relating to voltage is not applicable to test cells and batteries at fully discharged states. (Section 38.3.4.3.3)
T4 - Shock	This test simulates possible impacts during transport.	Test cells and batteries shall be secured to the testing machine by means of a rigid mount which will support all mounting surfaces of each test battery. Each cell shall be subjected to a half-sine shock of peak acceleration of 150gn and pulse duration of 6 milliseconds. Alternatively, large cells may be subjected to a half-sine shock of peak acceleration of 50gn and pulse duration of 11 milliseconds. Each battery shall be subjected to a half-sine shock of peak acceleration depending on the mass of the battery. The pulse duration shall be 6 milliseconds for small batteries and 11 milliseconds for large batteries. The formulas below are provided to	Cells and batteries meet this requirement if there is no leakage, no venting, no disassembly, no rupture and no fire and if the open circuit voltage of each test cell or battery after testing is not less than 90% of its voltage immediately prior to this procedure. The requirement relating to voltage is not applicable to test cells and batteries at

Test	Description	Procedure	Pass requirements
		calculate the appropriate minimum peak accelerations (section 38.3.4.4.2)	fully discharged states (section 38.3.4.4.3.)
T5 – External short circuit	This test simulates an external short circuit.	The cell or battery to be tested shall be heated for a period of time necessary to reach a homogeneous stabilized temperature of 57 ± 4 DC, measured on the external case. This period of time depends on the size and design of the cell or battery and should be assessed and documented. If this assessment is not feasible, the exposure time shall be at least 6 hours for small cells and small batteries, and 12 hours for large cells and large batteries. Then the cell or battery at 57 ± 4 DC shall be subjected to one short circuit condition with a total external resistance of less than 0.1 ohm. This short circuit condition is continued for at least one hour after the cell or battery external case temperature has returned to 57 ± 4 DC, or in the case of the large batteries, has decreased by half of the max temperature increase observed during the test and remains below that value. The short circuit and cooling down phases shall be conducted at least at ambient temperature (section 38.3.4.5.2)	Cells and batteries meet this requirement if their external temperature does not exceed 170 DC and there is no disassembly, no rupture and no fire during the test and within six hours after the test. (Section 38.3.4.5.3.)
T7 - Overcharge	This test evaluates the ability of a rechargeable battery or a single cell rechargeable battery to withstand an overcharge condition.	The charge current shall be twice the manufacturer's recommended max continuous charge current. The min voltage of the test shall be as follows: (a) when the manufacturer's recommended charge voltage is not more than 18 V, the min voltage of the test shall be the lesser of two times the max charge voltage of the battery or 22 V. (b) when the manufacturer's recommended charge voltage is more than 18 V, the min voltage of the test shall be 1.2 times the max charge voltage. Tests are to be conducted at ambient temperature. The duration of the test shall be 24 h (section 38.3.4.7.2)	Rechargeable batteries meet this requirement if there is no disassembly and no fire during the test and within seven days after the test (section 38.3.4.7.3)

3.0 SHIPPING AND PACKAGING OF BATTERIES

All photographs, documentation, and results have been performed by UL under contract.
For the procurement of LiB sets, SR provided UL with a list of 24 battery sets to procure, with direct online links to purchase, specific instruction to select the fastest shipping option, specific instruction to UL to create two separate orders for A, B, and C sets (one order under 5kg and the other order equal to or over 5kg), and an Inspection Checklist [Table 4].

3.1 Purchased Battery Sets

Table 6 summarizes the LiBs that were purchased for all 24 sets and the marketplace they were purchased from. The approximate shipping time represents the number of days from when the package entered the transportation system to when it left. Each box was assigned a number for tracking purposes.

While the sets were purchased as one small and one large order of LiBs, some suppliers sent all batteries in just a single package, while other suppliers sent multiple packages each containing a different number of LiBs. As well, all the marketplaces removed delivery date guarantees for shipping all items, regardless of the shipping type, due to logistical issues that occurred during of the COVID-19 pandemic. Due to this, a separate numbering system was used to identify the packages that came in. The pandemic also caused abnormal shipping times, such as expedited and air shipments taking longer than standard ground shipments, or two-day shipments taking 10 days.

A total of 44 packages were received. Based on how the packages were labelled, most shipments were likely sent by ground during the entire shipping cycle. Only three packages (3/44) had labels that indicated they were shipped by air. Ground shipments with low shipping times could not be suspected to be shipped by air due to the lack of air shipping labels and the possibility that the origin and destination of a shipment is within feasible limits.

Table 6: Package Weight and Shipping Times of Received Packages

Set ID	Marketplace	Cost / unit USD	Shipping Type	Received Packages			
				Box ID.	**No. of units**	**Approx. Ship Time**	**Package Weight**
A1	Market A (linked by OEM store)	$118.00	Standard Ground	A1-1 A1-2 A1-3 A1-4 A1-5 A1-6 A1-7 A1-8	2 2 8 3 3 1 3 3	7-12 days	2.135kg 2.214 kg 8.37 kg 3.235 kg 3.169 kg 1.122 kg 3.217 kg 3.215 kg
A2	Market B	$24.00	Standard Ground	A2-1	24	4 days	16.32 kg
A3	Market A	$24.00	Standard Ground	A3-1 A3-2	2 22	6 days	1.403 kg 14.63 kg
A4	Market C	$22.61	**Air**	A4-1 A4-2	23 2	6 days	15.87 kg 1.252 kg
A5	Market A	$29.50	Expedited (Ground)	A5	24	4 days	16.554 kg
A6	Market B	$24.00	Standard Ground	A6	24	6 days	16.02 kg
B1	Market D (linked by OEM store)	$105.19	Standard Ground	B1-1 B1-2 B1-3	4 20 1	1 day	2.185 kg 9.981 kg 0.652 kg
B2	Market B	$19.00	**Air**	B2-1	24	3 days	10.15 kg
B3	Market A	$23.95	Standard Ground	B3-1 B3-2	21 4	4 days	9.468 kg 1.934 kg
B4	Market B	$15.10	Standard Ground	B4-1 B4-2	20 4	2 days	9.044 kg 2.608 kg
B5	Market A	$19.50	Standard Ground	B5-1 B5-2 B5-3	8 12 4	5 days	3.589 kg 5.208 kg 1.859 kg
B6	Market C	$24.26	Seller's Decision (Likely Ground)	B6-1 B6-2 B6-3	4 10 11	4 days	1.647 kg 4.138 kg 4.665 kg
C1	Market A (linked by OEM store)	$62.45	Standard Ground	C1-1 C1-2	19 2	4 days	13.45 kg 1.475 kg
C2	Market A	$17.99	Standard Ground	C2-1 C2-2	19 2	2 days	8.247 kg 0.928 kg
C3	Market B	$18.50	Priority (Ground)	C3-1	18	5 days	7.571 kg
C4	Market B	$28.88	Standard Ground	C4-1	21	8 days	14.71 kg
C5	Market B	$21.99	Standard Ground	C5-1 C5-2	19 2	4 days	13.10 kg 1.320 kg
C6	Market C	$48.29	**Air**	C6-1	21	6 days	14.551 kg
D1	Market E (linked by OEM store)	$39.99	Two-Day (Ground)	D1-1	17	4 days	1.276 kg
D2	Market A	$13.99	Standard Ground	D2-1	17	2 days	1.827 kg
D3	Market B	$8.31	Standard Ground	D3-1	17	2 days	0.863 kg
D4	Market B	$7.99	Two-Day (Ground)	D4-1	17	10 days	0.996 kg
D5	Market C	$3.28	Standard Ground	D5-1	17	19 days	1.190 kg
D6	Market C	$15.39	Standard Ground	D6-1	17	13 days	1.052 kg

3.2 Damage from Incoming Packages and Compliance with Container Standard

The Transport Canada standard for small containers (TP 14850) specifies Packaging Instruction 903 that states, when shipping LiBs fully regulated by road or rail, they must be placed in a UN standardized container that meets the packing group II performance level, and secured to prevent inadvertent movement, protected against short circuit and the terminals must not support the weight of other superimposed elements [12]. The US has similar requirements for packaging (49 CFR 173.185(b)(3), 49 CFR 173.185(c)(2)). If the entire set met the criteria above, then it will be considered appropriate outer packaging. When answering question 8 of the inspection checklist (Do the batteries have sufficient protection within the outer package according to the packaging instructions?), UL found that many LiBs were not sufficiently packaged to prevent shocks, vibrations, and other types of abuse. Some LiBs were packaged in bubble wrap, some in blister packs, and others only had crumpled paper or no padding material at all. The summary of packaging and LiB damage observed is presented in Table 7.

Table 7: Damage Observed on Packages

Set ID	Market	Shipping Type	Appropriate Outer Packaging	Damage Observed
A1	Market A (linked by OEM store)	Standard Ground	No	4 boxes dented (see Figure *1*) One blister pack containing the battery was cracked and exposed the battery
A2	Market B	Standard Ground	No	-
A3	Market A	Standard Ground	Yes	Packing tape slightly damaged
A4	Market C	**Air**	Yes	-
A5	Market A	Expedited (Ground)	Yes	Box dented and appeared to be retaped
A6	Market B	Standard Ground	Yes	Box dented and torn
B1	Market D (linked by OEM store)	Standard Ground	Yes	Battery package damaged
B2	Market B	**Air**	Yes	-
B3	Market A	Standard Ground	No	Packing tape slightly damaged
B4	Market B	Standard Ground	Yes	-
B5	Market A	Standard Ground	Yes	-
B6	Market C	Seller's Decision (Likely Ground)	No	Three boxes slightly damaged Damage to the terminals on one battery
C1	Market A (linked by OEM store)	Standard Ground	Yes	Damage to outer and inner packaging. Retaped and torn in areas
C2	Market A	Standard Ground	Yes	Box dented
C3	Market B	Priority (Ground)	Yes	Several dents in box
C4	Market B	Standard Ground	Yes	Box dented and torn
C5	Market B	Standard Ground	Yes	Box dented and torn
C6	Market C	**Air**	Yes	-
D1	Market E (linked by OEM store)	Two-Day (Ground)	Yes	-
D2	Market A	Standard Ground	Yes	-
D3	Market B	Standard Ground	No	-
D4	Market B	Two-Day (Ground)	Yes	-
D5	Market C	Standard Ground	Yes	-
D6	Market C	Standard Ground	Yes	-

Sixteen packages (16/44, 36%) had suffered some form of damage upon receipt by the contractor. Most packages that received damage had dents and loose packing tape as observed in Figure *1*.

Figure 1: B6 Package (Box B6-1) is dented and appears to be retaped. Similar damage was observed for packages for A1, A3, A5, B1, B3, C1, C2, C3, C4, and C5.

Physical damage to the LiBs themselves was observed on two shipments. A1 Package (Box A1-3) had damage to the blister pack creating a mark on its terminals, and B6 Package (Box B6-1) had a dent to the terminals. These LiBs were removed from the samples to be tested.

Despite damage to various packages, it did not seem to correlate to failure during UN 38.3 testing. However, batteries that seemed to have had direct damage were removed from the samples prior to starting testing.

3.3 Package Labelling Compliance with Regulations

Different packaging and labeling are required depending on whether LiBs are shipped by air or ground, whether the LiBs are being shipped to Canada or USA, the type of LiB being shipped, the weight of the entire parcel being shipped, and the total energy of the individual LiBs. For this section, as the batteries were shipped to USA, the packaging (49 CFR 173.185(c)) and labelling (49 CFR 173.185(b)) requirements will be considered and should be referred to for complete and current regulations [13].

Both the power tool batteries and smartphone batteries are classified in Class 9 – Miscellaneous dangerous goods as UN3480: Lithium-ion batteries. There is a difference in packaging requirements between LiBs less than 100Wh (Sets B,C, and D), and LiBs greater than 100Wh (Set A)

Shipping Set A LiBs(LiBs greater than 100Wh) requires:

- Specific UN packaging
- Class 9 Lithium Battery label
- UN3480 label and proper shipping name
- If shipped for air transport: Cargo Aircraft Only label
- If shipped for air transport: Be shipped not exceeding 30% State of Charge
- And more, not relevant to this study

Shipping Set B, C, and D requires (LiBs less than 100Wh):

- Strong outer packaging
- Lithium Battery Mark
- Text marking that shipment is forbidden for transport aboard passenger aircraft
- If shipped for air transport: Cargo Aircraft Only label
- If shipped for air transport: Be shipped not exceeding 30% State of Charge

- If shipped for air transport between 2.7-100Wh: 2 batteries per package (set B, C)
- If shipped for air transport between 2.7-20Wh: 8 cells per package (set D)
- And more, not relevant to this study

Several flowcharts providing guidance on regulatory requirements for shipping lithium batteries by air mode are available such as the one prepared by the International Air Transport Association (IATA) [Figure 2].

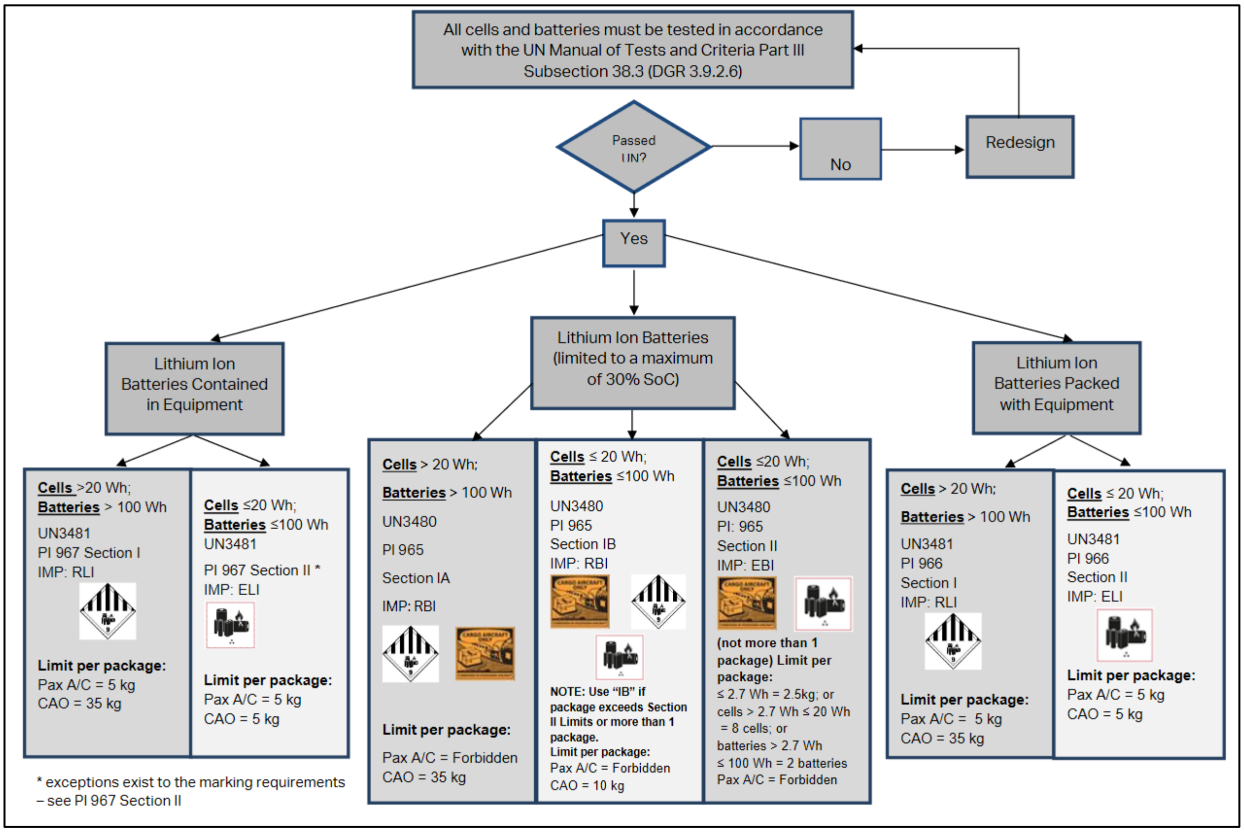


Figure 2: Regulatory Guidance Flowchart – Shipping Lithium-Ion Batteries by Air Mode [14]

Based on the images and inspections done by UL, twenty-three packages (23/44, 52%) were not shipped with the appropriate markings, with fifteen of those packages (15/23, 65%) being undeclared (no markings or indication that LiBs were inside the box). Out of all the marketplaces, only Market A was consistent in labelling compliance when shipping LiBs. Out of all the shipping couriers, all couriers had packages with non-compliant labelling. All the non-compliances are provided in Table 8: Package Labelling Non-Compliance.

Table 8: Package Labelling Non-Compliances

Set ID	Market	Shipping Type	Non-Compliances by at least one package in the set
A1	Market A (linked by OEM store)	Standard Ground	-
A2	Market B	Standard Ground	UNDECLARED: No Class 9 Lithium Battery label No UN3480 label No text marking indicating not permitted for transport by aircraft and vessel
A3	Market A	Standard Ground	-
A4	Market C	Air	UNDECLARED: No Class 9 Lithium Battery label Incorrect label (Shipped with UN3481 label which is for batteries contained in equipment and should be limited to the number of batteries needed to make the equipment operate) [Figure 5] The other box (A4-2) has no labels
A5	Market A	Expedited	-
A6	Market B	Standard Ground	UNDECLARED: No Lithium Battery Mark No text marking indicating not permitted for transport by aircraft and vessel
B1	Market D (linked by OEM store)	Standard Ground	UNDECLARED: No Lithium Battery Mark No text marking forbidden for transport aboard passenger aircraft
B2	Market B	Air	UNDECLARED: No Lithium Battery Mark No text marking forbidden for transport aboard passenger aircraft Package exceeded 10 kg, but was not shipped as fully regulated under ICAO Packing Instruction 965 Section IA.
B3	Market A	Standard Ground	-
B4	Market B	Standard Ground	Incorrect Lithium Battery Mark on outer package [Figure 3] Missing information on Lithium Battery Mark on internal packaging (no phone number) [Figure 4] No text mark indicating forbidden for transport aboard passenger aircraft or Cargo Aircraft Only label. Uses older version of the lithium battery mark that is no longer authorized
B5	Market A	Standard Ground	-
B6	Market C	Seller's Decision	UNDECLARED: No Lithium Battery Mark No text marking forbidden for transport aboard passenger aircraft OVERPACK does not appear on the outside of the overpack
C1	Market A (linked by OEM store)	Standard Ground	-
C2	Market A	Standard Ground	-
C3	Market B	Priority	UNDECLARED: No Lithium Battery Mark No text marking forbidden for transport aboard passenger aircraft
C4	Market B	Standard Ground	UNDECLARED: No Lithium Battery Mark No text marking indicating not permitted for transport by aircraft and vessel

Set ID	Market	Shipping Type	Non-Compliances by at least one package in the set
C5	Market B	Standard Ground	Battery label does not include UN3480 marking. Does not contain labeling to restrict transport aboard passenger aircraft. Uses older version of the lithium battery mark that is no longer authorized
C6	Market C	Air	Incorrect Lithium Battery Mark (UN3481) No Class 9 Lithium Battery label No Cargo Aircraft Only label
D1	Market E (linked by OEM store)	Two-Day	No text marking forbidden for transport aboard passenger aircraft
D2	Market A	Standard Ground	-
D3	Market B	Standard Ground	UNDECLARED: No Handling Label No text marking “Surface Mail Only, Batteries — Forbidden for Transportation Aboard Passenger Aircraft” or “Surface Mail Only, Lithium-ion Batteries — Forbidden for Transportation Aboard Passenger Aircraft.” Outer package not appropriate – uses flexible instead of rigid packaging Mail piece did not include the text “Batteries — Forbidden for Transportation Aboard Passenger Aircraft” or “Surface Mail Only, Lithium-ion Batteries — Forbidden for Transportation Aboard Passenger Aircraft.”
D4	Market B	Two-Day	UNDECLARED: No Lithium Battery Mark No text marking forbidden for transport aboard passenger aircraft
D5	Market C	Standard Ground	No Lithium Battery Mark No text marking forbidden for transport aboard passenger aircraft Outer packaging mentions package contains lithium-ion batteries, an outdated mark that is no longer authorized [Figure 6]
D6	Market C	Standard Ground	No Lithium Battery Mark No text marking forbidden for transport aboard passenger aircraft Outer packaging mentions package contains lithium-ion batteries, an outdated mark that is no longer authorized

Figure 3: Box B4-1 Is missing a UN3480 label, only the pictured marking was available

Figure 4: Box B4-1 internal packaging UN3480 label is missing a phone number

Figure 5: Box A4-1 with a UN3481 label

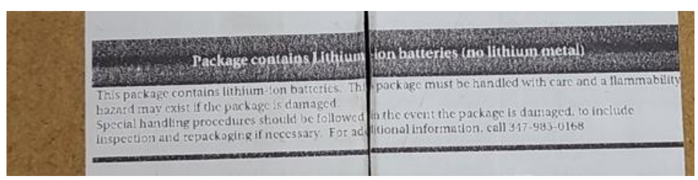


Figure 6: Box D6-1 only mentioning that package contains Lithium-ion batteries

3.4 UN 38.3 Test Summary Requests

In the study, UN 38.3 Test Summary reports were requested from the seller. There is no expectation for a seller to provide UN 38.3 Test Summary documents with each shipment, however they are required to “make available the test summary” when requested. When placing each order, UL attempted to request the Test Summary by including the request in the delivery instructions. UL also made a second attempt to contact the sellers (where their contact information was available) after receiving the packages and finding out the sellers did not provide any UN 38.3 test summary. No further attempts were made in contacting the seller or manufacturer. With these two attempts, many of the sellers that were able to be contacted failed to respond or stated that they were unable to provide one. Table 9 shows the results for all attempts.

Table 9: Test Summary Requests

Set ID	Market	Shipping Type	Attempt Results
A1	Market A (linked by OEM store)	Standard Ground	First attempt: Requested at time of purchase in delivery instructions. Second attempt: No way to contact after purchase.
A2	Market B	Standard Ground	Provided a Test Summary
A3	Market A	Standard Ground	First attempt: Requested at time of purchase in delivery instructions. Second attempt: No way to contact after purchase.
A4	Market C	**Air**	First attempt: Requested at time of purchase. Second attempt: The seller was contacted through marketplace's support / seller no longer existed to make request.
A5	Market A	Expedited	First attempt: Requested at time of purchase in delivery instructions. Second attempt: No way to contact after purchase.
A6	Market B	Standard Ground	First attempt: Requested at time of purchase. Second attempt: The seller was contacted through marketplace's support / seller no longer existed to make request.
B1	Market D (linked by OEM store)	Standard Ground	First attempt: No option available to make request. Second attempt: No way to contact seller after purchase.
B2	Market B	**Air**	No Test Summary on both first and second attempts
B3	Market A	Standard Ground	First attempt: Requested at time of purchase in delivery instructions. Second attempt: No way to contact after purchase.
B4	Market B	Standard Ground	First attempt: Requested at time of purchase. Second attempt: The seller was contacted through marketplace's support / seller no longer existed to make request.
B5	Market A	Standard Ground	First attempt: Requested at time of purchase in delivery instructions. Second attempt: No way to contact after purchase.
B6	Market C	Seller's Decision	First attempt: Requested at time of purchase. Second attempt: The seller was contacted through marketplace's support / seller no longer existed to make request.
C1	Market A (linked by OEM store)	Standard Ground	First attempt: Requested at time of purchase in delivery instructions. Second attempt: No way to contact after purchase.
C2	Market A	Standard Ground	First attempt: Requested at time of purchase in delivery instructions. Second attempt: No way to contact after purchase.
C3	Market B	Priority	Provided a Test Summary
C4	Market B	Standard Ground	First attempt: Requested at time of purchase. Second attempt: The seller was contacted through marketplace's support / seller no longer existed to make request.
C5	Market B	Standard Ground	First attempt: Requested at time of purchase. Second attempt: The seller was contacted through marketplace's support / seller no longer existed to make request.
C6	Market C	**Air**	Provided a Test Summary [Figure 7]
D1	Market E (linked by OEM store)	Two-Day	First attempt: Requested at time of purchase. Second attempt: The seller was contacted through marketplace's support / seller no longer existed to make request.
D2	Market A	Standard Ground	First attempt: Requested at time of purchase in delivery instructions. Second attempt: No way to contact after purchase.
D3	Market B	Standard Ground	First attempt: Requested at time of purchase. Second attempt: The seller was contacted through marketplace's support / seller no longer existed to make request.
D4	Market B	Two-Day	First attempt: Requested at time of purchase. Second attempt: The seller was contacted through marketplace's support / seller no longer existed to make request.
D5	Market C	Standard Ground	First attempt: Requested at time of purchase. Second attempt: The seller was contacted through marketplace's support / seller no longer existed to make request.
D6	Market C	Standard Ground	Provided a Test Summary

Four sellers provided a UN38.3 Test Summary (for sets A2, C3, C6, D6), however on closer inspection, only D6 test summary matched the battery packs purchased.

For the test summary provided for A2, it was observed that the image of the LiB label in the test summary did not match the LiB label for the samples that were received. The test summary also declares a voltage of 18.5 V instead of 20 V, and a battery weight of 624.5g while the lithium batteries that UL received weighed 597.3g (discussed later in Section 3.5 State of Charge (SOC) Compliance). With these discrepancies it appears that the UN 38.3 tested LiBs are in fact different from the LiBs that UL received. If there were changes to the construction of the LiB, clause 38.3.2.2(c) of UN Manual of Tests and Criteria 7th edition states “A change that would lead to failure of any of the tests, shall be considered a new type and shall be subjected to the required tests” [11]. The battery listed in A2 did not meet the other criteria for retesting (clause 38.3.2.2(b) “an increase in nominal voltage of more than 20%”), so retesting is left at the discretion of the manufacturer to make this determination.

For test summaries provided for C3 and C6, it was only for lithium cells and not the battery that was purchased so these test summaries were not correct [Figure 7]. It was also unknown if these test summaries were for the component cells that make up the battery or not. UL did not perform further examinations to determine if the test summaries matched the component cells of the batteries.

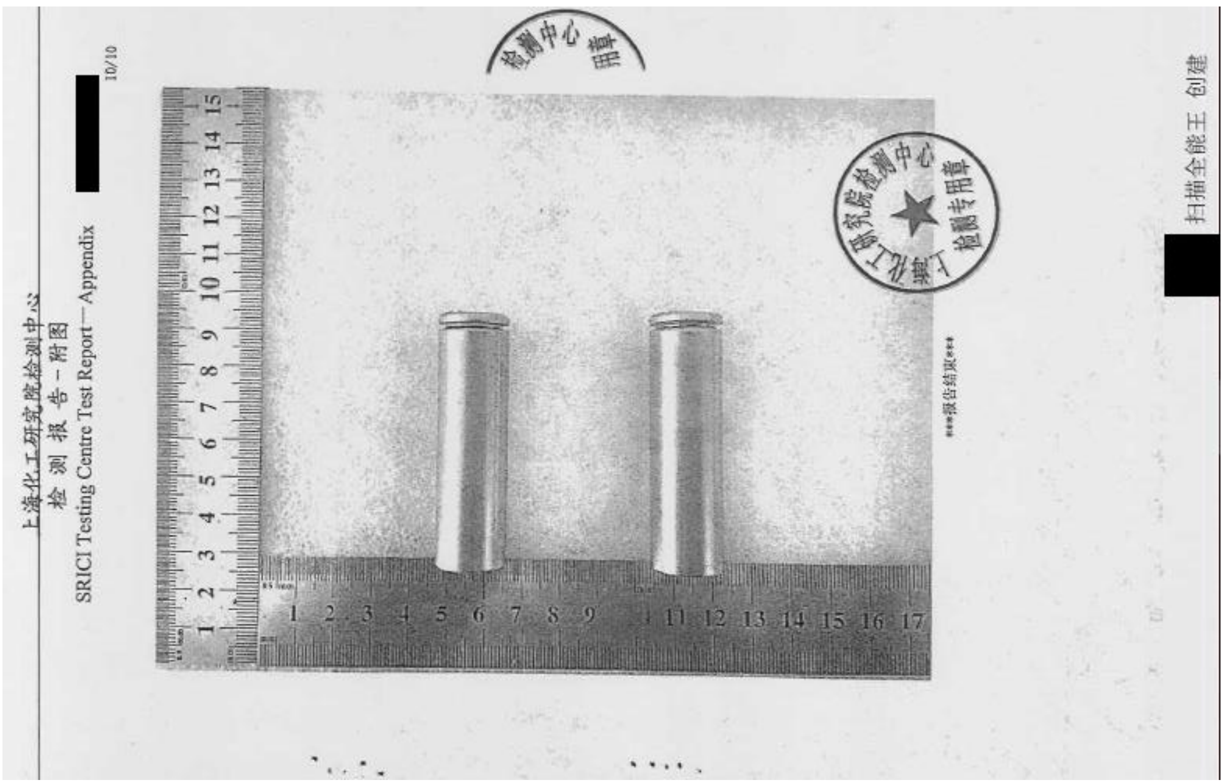


Figure 7: UN 38.3 Test Summary for C6, but only for a cell and not an entire battery pack

The test summary provided by D6 did match the battery purchased. However, when UL performed their UN 38.3 Tests, D6 did not pass. Details of the failure are specified in Section 4.10.

This study provides further evidence to support US DOT PHMSA’s concerns [1] with shippers being unable to provide valid test reports as required under UN 38.3, as UL attempted to ask for test summary reports but both the marketplace’s system and sellers failed to provide them in most cases.

3.5 State of Charge (SOC) Compliance

Lithium batteries that are shipped under UN3480 and transported by air mode are required to be at 30% SOC or lower. The lower SOC may provide an additional measure of safety during transport and reduce the likelihood of a thermal event [15].

In total, twenty-three (23/24) sets or 294/368 tested batteries had a state of charge above 30%. Only one set had all tested batteries with a measured SOC at 30% or lower, which belongs to the OEM B set. Every third-party replacement set had batteries that were tested to have a measured SOC higher than 30%, however there is no SOC requirement on ground-only shipments [Table 10]. Only three sets could be confirmed to have been shipped by air: A4, B2, and C6. These 3 sets are non-compliant based on this SOC requirement.

As an additional note, the measured capacities for the non-OEM replacement LiBs were generally lower than advertised. Set A4 advertised up to 10Ah of capacity but ended up with the lowest capacity out of the Set A LiBs at only 2.36 - 2.85Ah.

Table 10: State of Charge and measured specification

Set ID	Advertised Voltage/ Capacity	Measured State of Charge (SOC) upon arrival (%)	Number of LiBs with a SOC over 30% (Only applicable to sets shipped by air)	Measured Capacity (at first cycle) (Ah)	Measured Capacity (after 25 cycles) (Ah)	Measured Battery Weight (g)
A1	20V/6.0Ah	22 – 54	N/A	5.97 – 6.05	5.94 – 5.98	948.9
A2	20V/6.0Ah	2 – 89	N/A	2.54 – 4.11	2.53 – 4.23	597.3
A3	20V/6.0Ah	32 – 73	N/A	2.89 – 4.09	2.91 – 4.16	602.5
A4	20V/10.0Ah	1 – 45	14/16[b]	2.30 – 3.03	2.36 – 2.85	585.0
A5	20V/6.0Ah	40 – 53	N/A	5.13 – 5.20	4.98 – 5.08	616.9
A6	20V/6.0Ah	2 – 75	N/A	2.71 – 4.58	2.84 – 4.76	600.0
B1	12V/6.0Ah	27 – 29	N/A	5.65 – 5.87	5.44 – 5.51	425.6
B2	12V/6.0Ah	63 – 64	8/8[ab]	4.25 – 4.29	4.31 – 4.37	379.8
B3	12V/6.0Ah	5 – 65	N/A	5.11 – 5.35	5.17 – 5.36	386.4
B4	12V/6.0Ah	43 – 53	N/A	3.66 – 3.82	4.16 – 4.20	365.0
B5	12V/6.0Ah	31 – 35	N/A	4.10 – 4.20	4.15 – 4.33	368.9
B6	12V/6.0Ah	51 – 99	N/A	3.89 – 3.96	3.98 – 4.12	381.0
C1	20V/3Ah	15 – 34	N/A	2.91 – 3.10	2.91 – 3.03	614.0
C2	20V/3Ah	84 – 89	N/A	2.05 – 2.09	2.09 – 2.13	357.1
C3	20V/1.5Ah	50 - 70	N/A	1.30 – 1.39	1.28 – 1.39	325.5
C4	20V/7Ah	79 – 91	N/A	4.17 – 4.32	4.27 – 4.38	628.4
C5	20V/4Ah	57 - 62	N/A	3.60 – 3.83	3.77 – 3.86	613.0
C6	20V/3Ah	37 – 38	16/16[b]	2.94 – 3.00	2.99 – 3.02	579.0
D1	3.85V/3.08Ah	39 – 58	N/A	2.89 – 3.41	2.92 – 3.12	53.6
D2	3.85V/4.42Ah	42 – 60	N/A	3.92 – 4.24	3.92 – 4.23	56.3
D3	4.40V/3.2Ah	60 – 64	N/A	2.50 – 2.67	0 – 2.57	48.5
D4	3.85V/3.2Ah	18 – 48	N/A	1.14 – 1.64	0.41 – 1.39	42.0
D5	3.85V/3.2Ah	48 – 63	N/A	2.56 – 2.93	0 – 2.64	48.2
D6	3.85V/4.1Ah	44 – 56	N/A	3.83 – 4.14	3.82 – 4.13	55.6

[a] - Only half the samples were properly logged and recorded.
[b] - This set is reasonably considered to have been shipped by air, so this result would be a non-compliance.

4.0 UN 38.3 TESTING OF BATTERIES

UN 38.3 Testing was performed according to the UN Manual of Tests and Criteria, 7th edition. Tests T.1 to T.5 were conducted in sequence on the same batteries, followed by T.7. If one or more batteries in a set failed a test, that battery set was deemed non-compliant (NC). Typically testing would stop at that point, however for this study, regardless of NCs found in testing, failed batteries were removed from further testing and the remaining batteries from that set would move on to the next test.

Table 11: Overview of UN 38.3 Test Results

Set ID	Charge/ Discharge	T.1	T.2	T.3	T.4	T.5	T.7	UN 38.3Test Result
Power Tool Batteries								
A1 - OEM	✓	✓	✓	✓	✓	✓	✓	PASS
A2	✓	✓	✓	1 NC	✓	1 NC	✓	FAIL
A3	✓	✓	✓	3 NCs	✓	✓	✓	FAIL
A4	✓	✓	✓	✓	✓	5 NCs	7 NCs	FAIL
A5	✓	✓	✓	✓	✓	✓	✓	PASS
A6	✓	✓	✓	1 NC	✓	✓	✓	FAIL
B1 - OEM	✓	✓	✓	✓	✓	✓	✓	PASS
B2	✓	✓	✓	✓	✓	✓	4 NCs	FAIL
B3	✓	✓	✓	✓	✓	✓	✓	PASS
B4	✓	✓	✓	✓	✓	✓	✓	PASS
B5	✓	✓	✓	✓	✓	✓	✓	PASS
B6	✓	✓	✓	✓	✓	✓	✓	PASS
C1 - OEM	✓	✓	✓	✓	✓	✓	✓	PASS
C2	✓	✓	✓	✓	✓	1 NC	✓	FAIL
C3	✓	✓	✓	✓	✓	✓	✓	PASS
C4	✓	✓	✓	1 NC	✓	✓	✓	FAIL
C5	✓	✓	✓	1 NC	✓	✓	2 NCs	FAIL
C6	✓	✓	✓	7 NC	✓	✓	✓	FAIL
Smartphone Batteries								
D1 - OEM	✓	✓	✓	✓	✓	✓	✓	PASS
D2	✓	✓	✓	✓	✓	✓	✓	PASS
D3	✓	✓	✓	✓	✓	✓	✓	PASS
D4	✓	✓	✓	✓	✓	✓	✓	PASS
D5	✓	✓	✓	✓	✓	✓	✓	PASS
D6	✓	✓	✓	1 NC	✓	✓	✓	FAIL

✓ - All (Remaining) Batteries Compliant/Passing
NCs - Non-Compliances

All OEM batteries passed. Ten sets (10/24) tested were found to have NCs during UN 38.3 Testing. Non-compliances were found during T.3 – Vibration Testing, T.5 – Short Circuit Testing, and T.7 Overcharge Testing. Sets that failed T.5 and T.7 tended to have severe NCs (i.e., fire and explosion), while sets that failed T.3 were generally observed to have less severe NCs (i.e., voltage drop). The next sections will describe all the UN 38.3 failures observed with a focus on all the specific LiB samples that failed.

4.1 Non-Compliances on A2

The seller provided a UN 38.3 test summary stating compliance with the standard, however UL identified two (2) NCs while testing. This supports the observation in section 3.3 UN 38.3 Test Summary Requests that the summary report provided was for a different battery design.

T.3 Test Failure

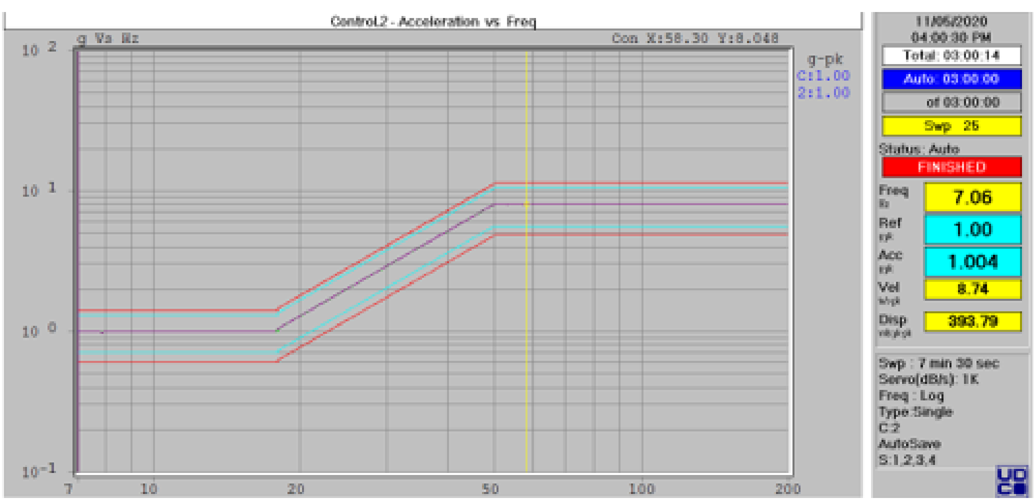
One battery (see sample 2 in Table 12) lost more than 10% of its voltage during the T.3. Vibration test. This is a failure criteria for the test, which resulted in NC.

The battery remained intact and there was no mass loss over 0.1g, no leakage, no venting, no disassembly, no rupture, and no fire. However, the battery did rattle when shaken after the test, which suggests the possibility of a broken internal weld or electrical connection within the battery pack's enclosure leading to the voltage loss.

Table 12: A2 T.3 Samples Test Results, failed samples in bold

Sample No.	Condition	Weight			Voltage		
		Before	After	% Loss	Before	After	% Remaining
9	1 cycle	572.41g	572.46g	0.00	20.49V	20.48 V	99.95
10	1 cycle	598.91g	598.95g	0.00	20.46 V	20.46 V	100
11	1 cycle	567.77g	567.82g	0.00	20.57 V	20.56 V	99.95
12	1 cycle	581.71g	581.76g	0.00	20.51 V	20.51 V	100
1	25 cycle	567.13g	567.18g	0.00	20.57 V	20.57 V	100
2	**25 cycle**	**618.80g**	**618.84g**	**0.00**	**20.58 V**	**16.01 V**	**77.79**
3	25 cycle	609.35g	609.43g	0.00	20.49 V	20.48 V	99.95
4	25 cycle	568.30g	568.36g	0.00	20.57 V	20.57 V	100

Vibration plots [Figure 8] show no difference in the parameters with tests that had compliant results and non-compliant results. This extends to all batteries that failed T.3 Vibration testing.



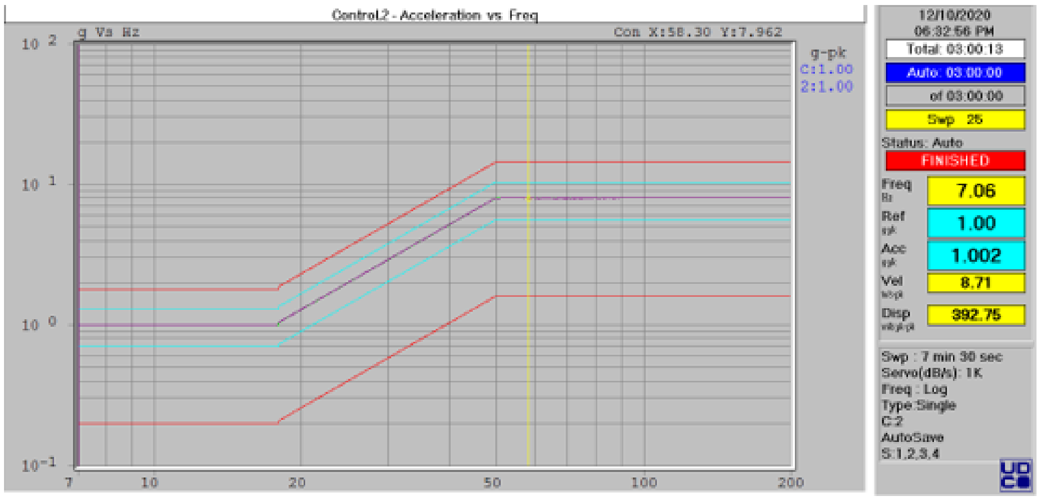


Figure 8: Acceleration vs. Frequency graph for (top) A1 Set A OEM and (bottom) A2 replacement. The set control – indicated with the purple line– show tests with both compliant and non-compliant batteries experience the same test parameters.

T.5 Test Failure

As a reminder, UN 38.3 testing goes in order from T.1 to T.5, and normally stops as soon as the first NC is spotted. Had the A2 (Market B) been a client for performing certification, the testing would have stopped at T.3. However, we continued the testing in the order described in UN 38.3 for research purposes.

One battery (see sample 4 in Table 13) had its surface temperature rise above 170°C during the T.5. External Short Circuit test. This is a failure criteria for the test, which resulted in NC.

Table 13: A2 T.5 Samples Test Results, failed samples in bold

Sample No.	Condition	Voltage Before Test	Maximum Surface Temperature	Total External Resistance	Maximum Measured Current	Comments
9	1 cycle	20.46V	80°C	88 mΩ	137A	No failure
10	1 cycle	20.45V	90°C	85 mΩ	141A	No failure
11	1 cycle	20.55V	84°C	85 mΩ	150A	No failure
12	1 cycle	20.49V	60°C	78 mΩ	N/A	Sample tripped before current recorded
1	25 cycle	20.57V	90°C	87 mΩ	156A	No failure
2	-	-	-	-	-	Removed at T.3
3	25 cycle	20.46V	84°C	84 mΩ	157A	No failure
4	**25 cycle**	**20.57V**	**170.4°C**	**79 mΩ**	**165A**	**Temperature exceeded**

The battery remained intact with no disassembly and no fire within six hours of the test. However, the plastic around the thermocouple and battery case terminals warped due to the rise in temperature [Figure 9]. Although this sample was less than a degree above the limit of 170°C for this test [Figure 10], it is still considered a non-compliant result. The max temperature for batteries that passed this test tended to be around 60°C, with the A1 OEM example [Figure 11]. Also of note is that other standards such as UL 2054 (Standard for Household and Commercial Batteries) have a temperature limit of 150°C for a very similar short circuit test.

Figure 9: A2 Sample 5 T.5. - Melting of the plastic case due to the heat generated during the test

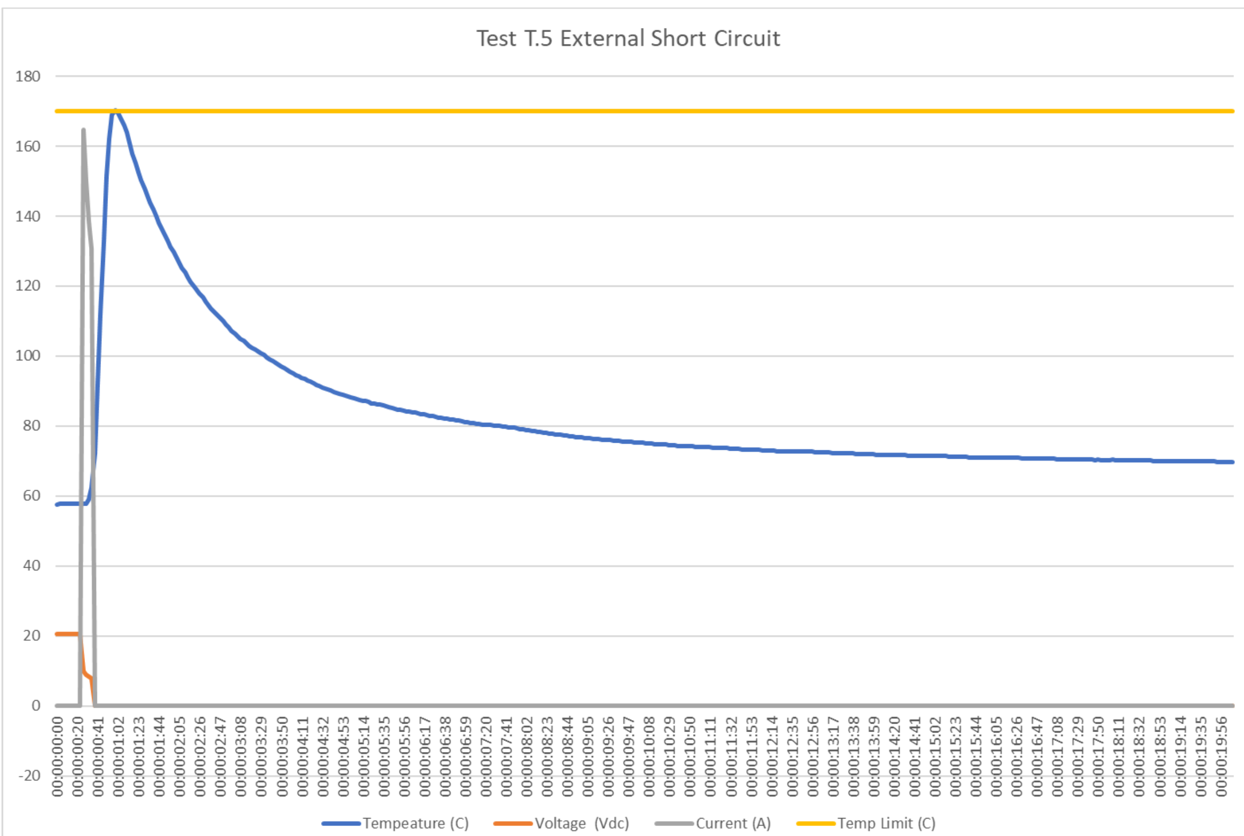


Figure 10: A2 Sample 4 Test T.5 failure with temperature rising past 170C

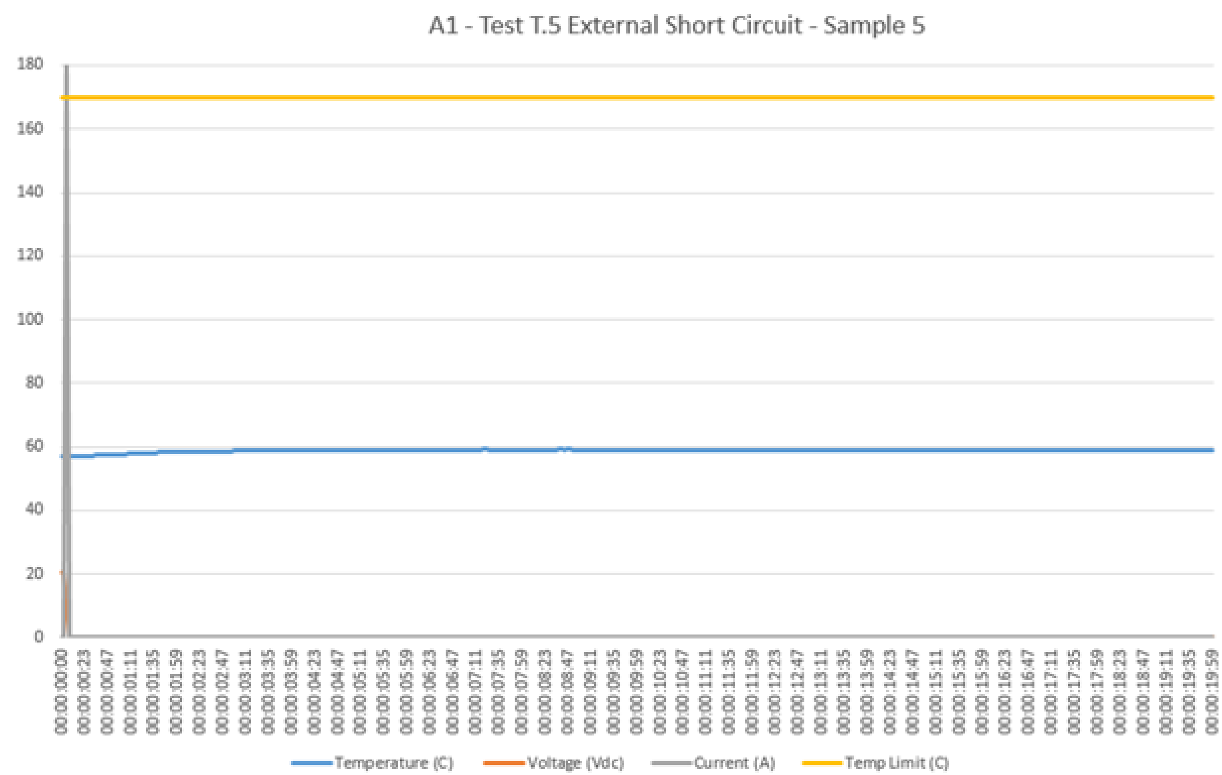


Figure 11: A1 Sample 5 passing the T.5. External Short Circuit Test. Temperature stays well below 170C.

4.2 Non-Compliances on A3

T.3 Test Failure

Three batteries lost more than 10% of their voltage during the T.3. Vibration test. This is a failure criteria for the test, which resulted in NC.

All batteries remained intact and there was no mass loss over 0.1g, no leakage, no venting, no disassembly, no rupture, and no fire. However, the batteries did rattle when shaken after the test, which suggests the possibly of a broken internal weld or electrical connection within the battery pack's enclosure leading to the voltage loss.

Table 14: A3 T.3 Samples Test Results, failed samples in bold

Sample No.	Condition	Weight			Voltage		
		Before	After	% Loss	Before	After	% Remaining
9	1 cycle	603.93g	603.99g	0.00	20.55V	20.54V	99.95
10	1 cycle	602.47g	602.54g	0.00	20.54V	20.53V	99.95
11	1 cycle	600.80g	600.83g	0.00	20.52V	20.51V	99.95
12	1 cycle	601.63g	601.68g	0.00	20.51V	20.50V	99.95
1	**25 cycles**	**614.93g**	**614.88g**	**0.01**	**20.72V**	**11.58V**	**55.89**
2	**25 cycles**	**602.90g**	**602.94g**	**0.00**	**20.54V**	**15.96V**	**77.70**
3	25 cycles	602.77g	602.82g	0.00	20.59V	20.58V	99.95
4	**25 cycles**	**602.19g**	**602.23g**	**0.00**	**20.58V**	**16.00V**	**77.75**

Vibration plots have been omitted, as the conclusions are the same for the A2 T.3 Test failure.

4.3 Non-Compliances on A4

T.7 Test Failure

Seven batteries caught on fire and exploded during the T.7 Overcharge Test. One sample (Sample 5) did not catch on fire or explode but was disconnected from the test by the blast of the other samples.

Table 15: A4 T.7 Samples Test Results, failed samples in bold

Sample No.	Condition	Voltage Before Test	Measured Overcharge Current	Comments
13	**1 cycle**	**20.63 V**	**8805 mA**	**Fire & Explosion**
14	**1 cycle**	**17.14 V**	**8802 mA**	**Fire & Explosion**
15	**1 cycle**	**20.65 V**	**8808 mA**	**Fire & Explosion**
17	**1 cycle**	**20.84 V**	**8802 mA**	**Fire & Explosion**
5	25 cycle	20.67 V	8807 mA	No fire: Sample came disconnected from a blast of another
6	**25 cycle**	**20.68 V**	**8810 mA**	**Fire & Explosion**
7	**25 cycle**	**20.62 V**	**8807 mA**	**Fire & Explosion**
8	**25 cycle**	**20.67 V**	**8800 mA**	**Fire & Explosion**

Figure 12 shows the overcharge causing the current to rise and lead to subsequent failure, while Figure 13 shows what a passing test would look like with B1 OEM sample.

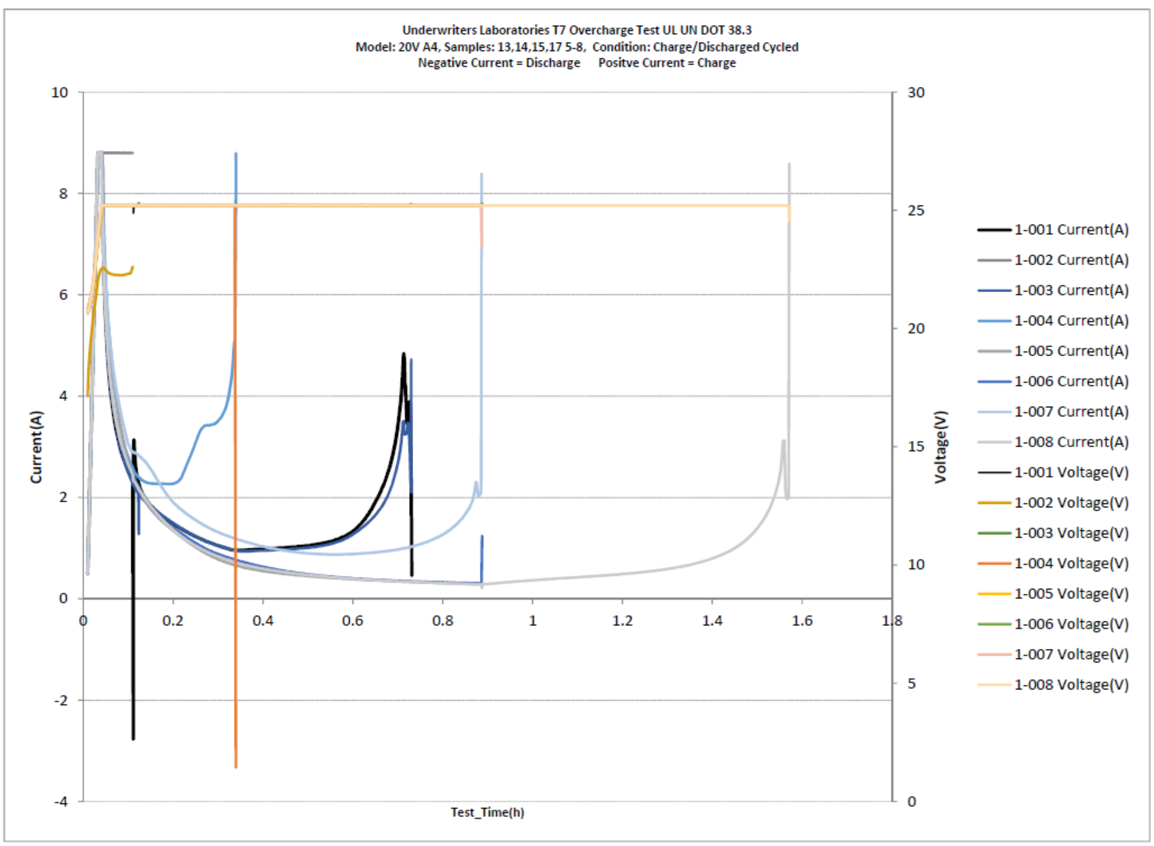


Figure 12: A4 Samples failing with current continuing to rise with overcharge

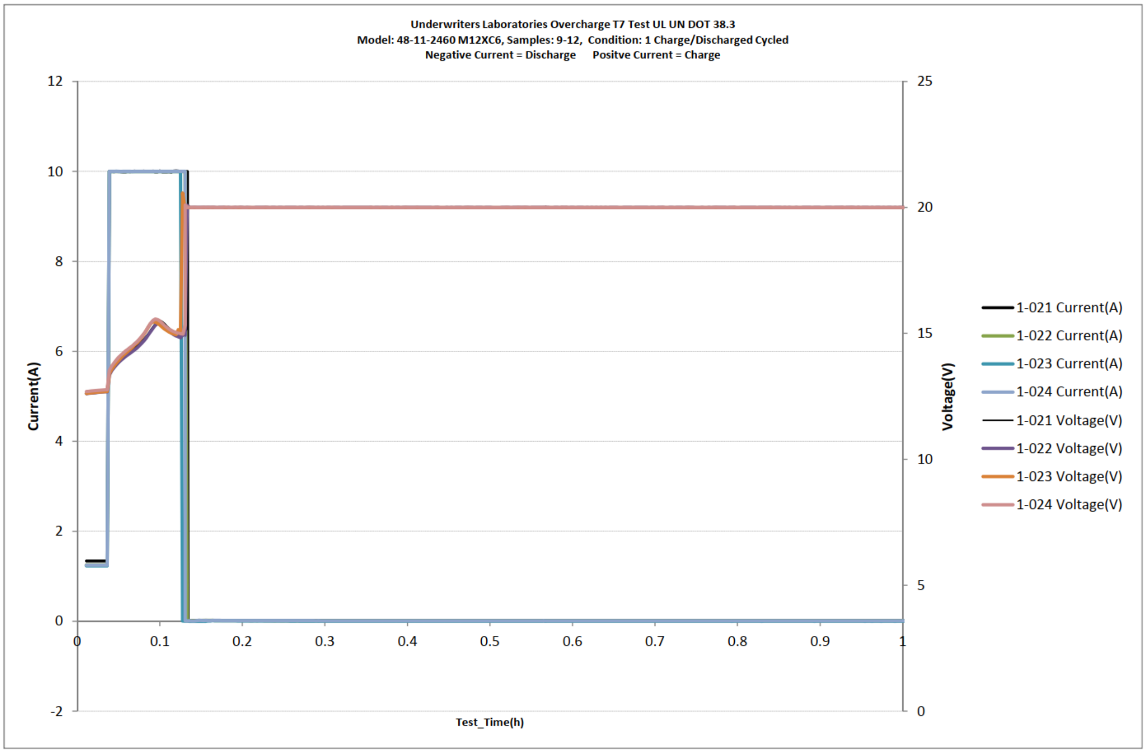


Figure 13: B1 Samples passing the Overcharge Test

Photographs of the exploded batteries [Figure 14, Figure 15] were taken to show the extent to the failure. A lot of smoke was present with most of the cells charred.

Figure 14: A4 Samples releasing a heavy amount of smoke after catching fire and exploding during the T.7 overcharge test

Figure 15: A4 Samples showing charring during the T.7 overcharge test

T.5 Test Failure

As a reminder, UN 38.3 splits sixteen batteries into two groups of eight batteries: eight go through Tests T.1 to T.5, while the other eight go through T.7 simultaneously. As tests T.1 to T.5 need to be done in order, T.7 typically finishes before T.5 starts. Normally testing will stop as soon as the first NC is spotted. Had the A4 (Market C) been a client for performing certification, the testing would have stopped during the T.7 failure. However, we continued the testing in the order described in UN 38.3, for research purposes.

Five batteries caught on fire and exploded during the T.5 External Short Circuit test, failing the test. Figure 16 shows the voltage spikes.

Table 16: A4 T.5 Samples Test Results, failed samples in bold

Sample No.	Condition	Voltage Before Test	Maximum Temperature	Total External Resistance	Maximum Measured Current	Comments
9	1 cycle	20.16V	87°C	88 mΩ	78A	No failure
10	**1 cycle**	**20.17V**	**260°C**	**81 mΩ**	**87A**	**Fire & Explosion**
11	**1 cycle**	**20.15V**	**144°C**	**89 mΩ**	**88A**	**Fire & Explosion**
16	1 cycle	20.16V	82°C	78 mΩ	95A	No failure
1	**25 cycles**	**20.06V**	**219°C**	**89 mΩ**	**76A**	**Fire & Explosion**
2	**25 cycles**	**20.05V**	**345°C**	**82 mΩ**	**76A**	**Fire & Explosion**
3	**25 cycles**	**20.08V**	**431°C**	**89 mΩ**	**75A**	**Fire & Explosion**
4	25 cycles	20.10V	74°C	77 mΩ	95A	No failure

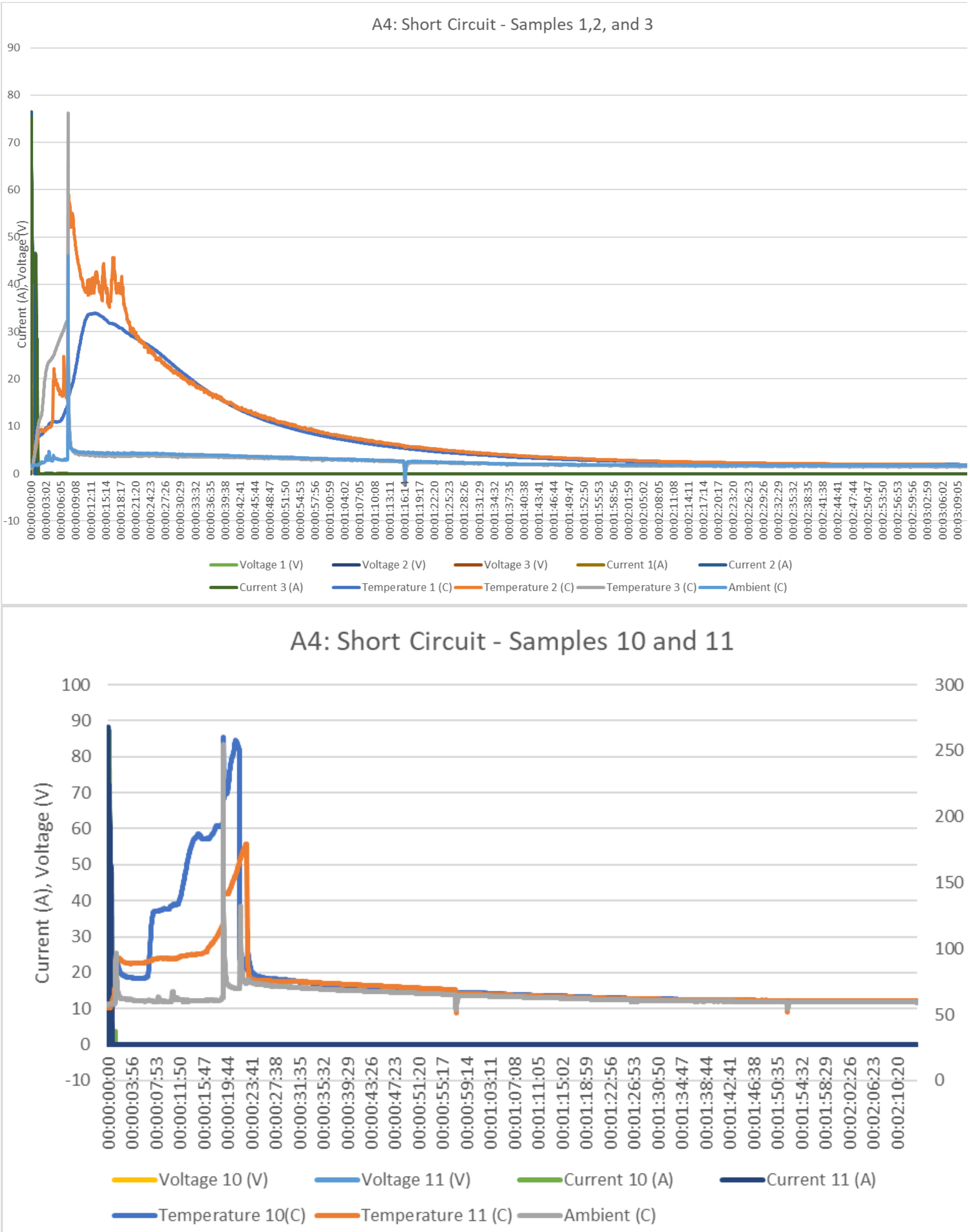


Figure 16: A4 Samples – T.5 Voltage-Current Graphs

Figure 17 shows the extent of the explosion and fire. A sample from each A4 package and both charge conditions resulted in severe failure. One cell/battery built up enough energy and exploded during the test with such force to dent the door of the explosion proof oven. The failure also had very audible popping noises during the test.

Figure 17: One A4 battery exploded with such force it dented the door of the explosion proof oven.

4.4 Non-Compliances on A6

T.3 Test Failure

One battery (see sample 3 in Table 17) lost more than 10% of its voltage during the T.3. Vibration test. This is a failure criteria for the test, which resulted in NC.

The battery remained intact and there was no mass loss over 0.1g, no leakage, no venting, no disassembly, no rupture, and no fire. However, the batteries did rattle when shaken after the test, which suggests the possibility of a broken internal weld or electrical connection within the battery pack's enclosure leading to the voltage loss.

Table 17: A6 T.3 Samples Test Results, failed samples in bold

Sample No.	Condition	Weight			Voltage		
		Before	After	% Loss	Before	After	% Remaining
9	1 cycle	567.94g	567.95g	0.00	20.58V	20.58V	100
10	1 cycle	604.32g	604.36g	0.00	20.51V	20.51V	100
11	1 cycle	603.07g	603.10g	0.00	20.52V	20.51V	100
12	1 cycle	591.11g	591.11g	0.00	20.60V	20.60V	100
1	25 cycles	600.48g	600.53g	0.00	20.61V	20.61V	100
2	25 cycles	608.82g	608.66g	0.03	20.45V	20.44V	100
3	**25 cycles**	**567.78g**	**567.79g**	**0.00**	**20.59V**	**7.00V**	**34.0**
4	25 cycles	610.39g	610.39g	0.00	20.36V	20.36V	100

Vibration plots have been omitted, as the graphs are similar, and the conclusions are the same for the A2 T.3 Test failure noted in section 4.1.

4.5 Non-Compliances on B2

T.7 Test Failure

Four samples caught on fire and exploded during the T.7 Overcharge Test.

Table 18: B2 T.7 Samples Test Results, failed samples in bold

Sample No.	Condition	Voltage Before Test	Measured Overcharge Current	Comments
13	**1 cycle**	**12.48 V**	**10010 mA**	**Fire & Explosion**
14	**1 cycle**	**12.43 V**	**10003 mA**	**Fire & Explosion**
15	**1 cycle**	**12.47 V**	**10011 mA**	**Fire & Explosion**
16	**1 cycle**	**12.47 V**	**10008 mA**	**Fire & Explosion**
5	25 cycle	12.47 V	10008 mA	No failure
6	25 cycle	12.48 V	10004 mA	No failure
7	25 cycle	12.48 V	10008 mA	No failure
8	25 cycle	12.49 V	10007 mA	No failure

Like A4, the fire and explosion left a lot of char and debris in the test chamber [Figure 18]. The voltage-current graph shows the spike in voltage/drop in current at the time of failure [Figure 19].

Figure 18: B2 Sample 13, 14, 15, 16 – T.7 photographs showing a lot of debris from the explosion

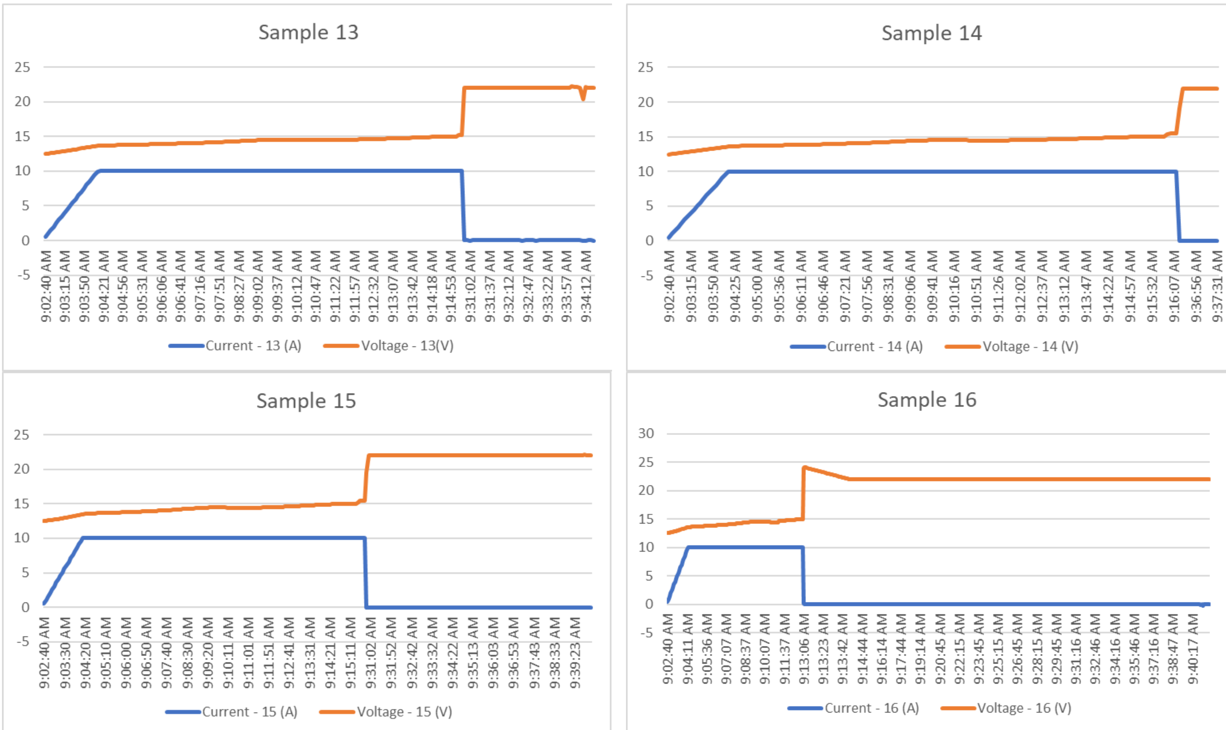


Figure 19 : B2 Sample 13,14,15,16 – T.7 Voltage-Current Graphs

4.6 Non-Compliances on C2

T.5 Test Failure

One battery caught on fire and exploded, failing the test. Three other batteries opened and leaked electrolyte, but UL did not consider this a non-compliance according to UN 38.3, section 38.3.4.5.3. Leakage is specified as a failure criteria for T.1, T.2, T.3, and T.4.

Table 19: C2 T.5 Samples Test Results, failed samples in bold

Sample No.	Condition	Voltage Before Test	Maximum Temperature	Total External Resistance	Maximum Measured Current	Comments
1 (Box C2-2)	1 cycle	20.52 V	116°C	81 mΩ	93.76 A	Sample leaked electrolyte
1 (Box C2-1)	1 cycle	20.50 V	79°C	82 mΩ	92.75 A	No failure
2 (Box C2-1)	1 cycle	20.51 V	435°C*	83 mΩ	100.51 A	No failure*
3	**1 cycle**	**20.52 V**	**356°C**	**88 mΩ**	**105.34 A**	**Fire and explosion**
2 (Box C2-2)	25 cycle	20.52 V	68°C	85 mΩ	117.77 A	No failure
8	25 cycle	20.56 V	103°C	83 mΩ	96.92 A	No failure
9	25 cycle	20.54 V	95°C	83 mΩ	100.19 A	Sample leaked electrolyte
10	25 cycle	20.54 V	72°C	87 mΩ	107.53 A	Sample leaked electrolyte

* Thermocouple was incorrectly placed, which is why the recorded temperature is high but did not catch on fire or explode. The actual maximum temperature of this sample was not recorded.

4.7 Non-Compliances on C4

T.3 Test Failure

One battery lost more than 10% of their voltage during the T.3. Vibration test. This is a failure criteria for the test, which resulted in NC.

The battery remained intact and there was no mass loss, no leakage, no venting, no disassembly, no rupture, and no fire. However, the battery did rattle when shaken after the test, which suggests the possibly of a broken internal weld or electrical connection within the battery pack's enclosure leading to the voltage loss.

Table 20: C4 T.3 Samples Test Results, failed samples in bold

Sample No.	Condition	Weight			Voltage		
		Before	After	% Loss	Before	After	% Remaining
1	1 cycle	628.86g	629.02g	0.00	20.57V	20.57V	100
2	1 cycle	628.94g	629.02g	0.00	20.57V	20.56V	100
3	1 cycle	631.97g	632.08g	0.00	20.60V	20.59V	100
4	1 cycle	628.68g	628.80g	0.00	20.55V	20.55V	100
9	25 cycle	628.84g	628.97g	0.00	20.58V	20.57V	100
10	**25 cycle**	**630.69g**	**630.74g**	**0.00**	**20.60V**	**16.10V**	**78.2**
11	25 cycle	632.15g	632.28g	0.00	20.61V	20.60V	100
12	25 cycle	628.19g	628.32g	0.00	20.59V	20.59V	100

4.8 Non-Compliances on C5

T.3 Test Failure

Two batteries lost more than 10% of their voltage during the T.3. Vibration test. This is a failure criteria for the test, which resulted in NC.

All batteries remained intact and there was no mass loss over 0.1g, no leakage, no venting, no disassembly, no rupture, and no fire. However, the batteries did rattle when shaken after the test, which suggests the possibly of a broken internal weld or electrical connection within the battery pack's enclosure leading to the voltage loss.

Table 21: C5 T.3 Samples Test Results, failed samples in bold

Sample No.	Condition	Weight			Voltage		
		Before	After	% Loss	Before	After	% Remaining
1 (Box C5-2)	1 cycle	613.58g	613.75g	+0.03	20.52V	20.48V	99.8
1 (Box C5-1)	1 cycle	612.47g	612.64g	+0.03	20.51V	20.47V	99.8
2 (Box C5-2)	**1 cycle**	**609.98g**	**610.15g**	**+0.03**	**20.52V**	**7.09V**	**34.6**
3	**1 cycle**	**610.94g**	**611.10g**	**+0.03**	**20.52V**	**16.01V**	**78.0**
2 (Box C5-1)	25 cycle	611.80g	611.97g	+0.03	20.55V	20.53V	99.9
8	25 cycle	612.58g	612.73g	+0.02	20.54V	20.52V	99.9
9	25 cycle	614.23g	614.35g	+0.02	20.56V	20.54V	99.9
10	25 cycle	612.27g	612.45g	+0.03	20.56V	20.53V	99.9

T.7 Test Failure

One battery caught on fire and exploded during this test.

Table 22: C5 T.7 Samples Test Results, failed samples in bold

Sample No.	Condition	Voltage Before Test	Measured Overcharge Current	Comments
4	1 cycle	20.83V	3987 mA	No failure
5	1 cycle	20.85V	3982 mA	No failure
6	1 cycle	20.62V	3992 mA	No failure
7	1 cycle	20.84V	3985 mA	No failure
11	25 cycle	20.93V	3977 mA	No failure
12	25 cycle	20.92V	3993 mA	No failure
13	25 cycle	20.94V	3994 mA	No failure
14	**25 cycle**	**20.92V**	**3998 mA**	**Fire & Explosion**

4.9 Non-Compliances on C6

T.3 Test Failure

Seven batteries lost more than 10% of their voltage during the T.3. Vibration test. This is a failure criteria for the test, which resulted in NC.

All batteries remained intact and there was no mass loss over 0.1g, no leakage, no venting, no disassembly, no rupture, and no fire. However, the batteries did rattle when shaken after the test, which suggests the possibly of a broken internal weld or electrical connection within the battery pack's enclosure leading to the voltage loss.

Table 23: C6 T.3 Samples Test Results, failed samples in bold

Sample No.	Condition	Weight			Voltage		
		Before	After	% Loss	Before	After	% Remaining
1	**1 cycle**	**577.78 g**	**577.85 g**	**0.00**	**20.47 V**	**0.00 V**	**0**
2	**1 cycle**	**579.33 g**	**579.42 g**	**0.00**	**20.47 V**	**1.05 V**	**5.1**
3	**1 cycle**	**579.56 g**	**579.56 g**	**0.00**	**20.47 V**	**15.59 V**	**76.2**
4	**1 cycle**	**578.05 g**	**578.11 g**	**0.00**	**20.47 V**	**3.58 V**	**17.5**
9	**25 cycle**	**578.16 g**	**578.24 g**	**0.00**	**20.52 V**	**15.64 V**	**76.2**
10	**25 cycle**	**578.96 g**	**579.03 g**	**0.00**	**20.52 V**	**15.74 V**	**76.7**
11	25 cycle	578.68 g	578.70 g	0.00	20.53 V	20.52 V	100
12	**25 cycle**	**580.04 g**	**580.08 g**	**0.00**	**20.52 V**	**15.63 V**	**76.2**

4.10 Non-Compliances on D6

T.3 Test Failure

One battery lost more than 0.1g of its weight during the T.3. Vibration test. This is a failure criteria for the test, which resulted in NC.

The battery remained intact and there was no significant voltage loss, no leakage, no venting, no disassembly, no rupture, and no fire. There was also a small tear in the pack after the test which may have caused the weight loss.

Table 24: D6 T.3 Samples Test Results, failed samples in bold

Sample No.	Condition	Weight			Voltage		
		Before	After	% Loss	Before	After	% Remaining
1	**1 cycle**	**55.134g**	**55.056g**	**0.14**	**4.32V**	**4.31V**	**99.8**
2	1 cycle	54.983g	54.991g	0.00	4.31V	4.31V	100
3	1 cycle	56.448g	56.455g	0.00	4.31V	4.31V	100
4	1 cycle	55.443g	55.450g	0.00	4.31V	4.31V	100
9	25 cycle	55.007g	55.016g	0.00	4.32V	4.31V	99.8
10	25 cycle	55.072g	55.078g	0.00	4.32V	4.32V	100
11	25 cycle	56.501g	56.509g	0.00	4.31V	4.31V	100
12	25 cycle	55.451g	55.458g	0.00	4.32V	4.32V	100

4.11 Additional Test Results of Interest

The following sets passed the UN 38.3 Tests, however due to how close the batteries were from failure they will usually be pointed out to clients during UN 38.3 certification testing. This is because the testing could indicate a potential issue or may fail other safety standards the product is being evaluated against other than the UN 38.3 test being prescribed.

T.5 Test Result – Concerns for A5, C3, D3, D4, D5

The criteria for a battery to pass T.5 requires it to, for a period of 6 hours after being subjected to an external short circuit:

- External temperature does not exceed 170°C
- No disassembly (rupture of battery where solid components are ejected)
- No rupture (mechanical fail of battery case, resulting in exposure or spillage of solid components)
- No fire (flames emitted from the battery)

During the T.5 short circuit test for A5 and C3, part of the battery case melted but was still compliant. For D3, D4, and D5, some charring occurred on the terminal ends, but the tests were compliant. A typical client asking for a UN 38.3 Test to be done on these batteries would have been informed of potential issues, but the tests will still be marked as passed.

T.7 Test Result – Concerns for B1

The criteria for a battery to pass T.7 requires it to, for a period of 7 days after being subjected to an overcharge:

- No disassembly (rupture of battery where solid components are ejected)
- No fire (flames emitted from the battery)

During the T.7 overcharge test for B1, all samples vented and leaked, but was still compliant as there was no disassembly or fire that occurred because of venting. The test result is interesting since all other compliant battery sets did not experience a vent condition during T.7. Again, this result would have been highlighted to any potential client as this result could become an issue for a different safety standard.

5.0 OBSERVATIONS

The purpose of this project was to understand the risks posed by LiBs, with particular focus on common consumer replacement batteries shipped by air, including third-party (non-OEM) replacement batteries. As the criteria to establish which LiBs could be considered substandard would be its ability to pass the UN 38.3 Tests, this is the primary NC we are concerned about. Other NCs (evidence of UN 38.3 testing prior to transport, labelling, packaging, and state of charge) were used to establish trends in substandard batteries. A summary of all the NCs, documentation and observations are found with the UN 38.3 Test results in bold [Table 25].

All LiB sets had at least one non-compliance (NC) in either UN 38.3 Testing, or packaging and labelling requirements for transportation. While there is an assumption that OEMs would ensure to uphold their brand with their batteries (and therefore adhere to all standards and regulations), the study showed that the couriers and/or marketplaces may not be transporting those batteries following regulations. All OEM batteries testing in this study passed the UN 38.3 tests, while half of the third-party sets failed.

UN 38.3 Test Summaries are required upon request as part of paragraph 38.3.5 of the UN Manual of Tests and Criteria [11]. We were only able to obtain UN 38.3 Test Summaries for 4 out of the 24 LiB sets, and only one test summary matched the product, but this set went on to fail the UN 38.3 tests anyway. During testing of these four sets, it was found that there were NCs with UN 38.3 despite the test summary that was received stating that the battery pack (or component cell if that was what the Test Summaries were) passed all required tests.

Twenty-three packages (23/44, 52%) were not shipped with the appropriate LiB markings, and fifteen of these packages were undeclared. Two of the 4 OEM sets contained packages with some labelling non-compliances. The high number of packages being shipped with missing or incorrect labelling may indicate that there may be a higher volume of LiBs in the transportation system (both standard and substandard) than what has been declared.

All LiB sets that were confirmed to be shipped by air (A4, B2, and C6) were non-compliant with the maximum 30% SOC limit requirement for air shipments, and also failed UN 38.3 testing.

Table 25: Overall results by battery set

Set ID	Marketplace	Shipped by	UN 38.3 Test Summary	Labelling & Packaging	# of LiB above 30% SOC	UN 38.3 Test Result
A1	Market A (linked by OEM store)	Standard Ground	Not Received	Compliant	N/A	**Pass**
A2	Market B	Standard Ground	Received: Possibly Invalid	Compliant	N/A	**Fail 2 NC**
A3	Market A	Standard Ground	Not Received	Compliant	N/A	**Fail 3 NC**
A4	Market C	**Air**	Not Received	**NC**	**14/16 NC***	**Fail 12 NC w/ Fire & Explosion**
A5	Market A	Expedited (Ground)	Not Received	Compliant	N/A	**Pass**
A6	Market B	Standard Ground	Not Received	Compliant	N/A	**Fail 1 NC**
B1	Market D (linked by OEM store)	Standard Ground	Not Received	**NC**	N/A	**Pass**
B2	Market B	**Air**	Not Received	**NC**	**8/8 NC*^**	**Fail 4 NC w/ Fire & Explosion**
B3	Market A	Standard Ground	Not Received	Compliant	N/A	**Pass**
B4	Market B	Standard Ground	Not Received	**NC**	N/A	**Pass**
B5	Market A	Standard Ground	Not Received	Compliant	N/A	**Pass**
B6	Market C	Seller's Decision (Likely Ground)	Not Received	**NC**	N/A	**Pass**
C1	Market A (linked by OEM store)	Standard Ground	Not Received	Compliant	N/A	**Pass**
C2	Market A	Standard Ground	Not Received	Compliant	N/A	**Fail 1 NC w/ Fire & Explosion**
C3	Market B	Priority (Ground)	Received: Possibly Invalid	**NC**	N/A	**Pass**
C4	Market B	Standard Ground	Not Received	**NC**	N/A	**Fail 1 NC**
C5	Market B	Standard Ground	Not Received	**NC**	N/A	**Fail 3 NC w/ Fire & Explosion**
C6	Market C	**Air**	Received: Possibly Invalid	**NC**	**16/16 NC***	**Fail 7 NC**
D1	Market E (linked by OEM store)	Two-Day (Ground)	Not Received	**NC**	N/A	**Pass**
D2	Market A	Standard Ground	Not Received	Compliant	N/A	**Pass**
D3	Market B	Standard Ground	Not Received	**NC**	N/A	**Pass**
D4	Market B	Two-Day (Ground)	Not Received	**NC**	N/A	**Pass**
D5	Market C	Standard Ground	Not Received	**NC**	N/A	**Pass**
D6	Market C	Standard Ground	Received	**NC**	N/A	**Fail 1 NC**

*: non-compliance as they were likely shipped by air
^: Only eight of sixteen samples were properly logged and recorded by the contractor.

5.1 Trends in UN 38.3 Non-Compliances

The results of this study were assessed to see if any trends regarding likelihood of non-compliance with UN 38.3 requirements could be established between factors such as:

- Package weight and visible damage during shipment
- Package labelling compliance
- Transportation mode
- OEM vs third-party replacement LiBs
- LiB model type (voltage/amperes)
- The marketplace where the LiBs are sold
- The shipping company responsible for transporting the LiBs

Package Weight and Visible damage during shipment Comparison

LiB were ordered as a “small” and “large” shipment size for comparisons of handling conditions form a previous study, however shippers did not honour the orders and would ship batteries in just a large package or several smaller ones (see Table 6) meaning there is no full comparison that can be made between small and large packages.

In this study, damage during shipment included dents to the outer packaging and ripped tape. The UN 38.3 testing non-compliance rate of the tested LiBs coming from damaged packages is the same as the ones where no damage is documented. Based on the fact undamaged packages resulted in failures, and damaged packages resulted in passing results, package conditions at receipt does not appear to correlate to the UN 38.3 testing results.

Table 26: UN 38.3 Test non-compliances by damage condition (Failed sets in bold)

Damage	Sets		UN 38.3 NC	NC Rate
Damage Documented	A1	B6	5 / 12	42%
	A3	C1		
	A5	**C2**		
	A6	C3		
	B1	**C4**		
	B3	**C5**		
No Damage Documented	**A2**	D1	5 / 12	42%
	A4	D2		
	B2	D3		
	B4	D4		
	B5	D5		
	C6	**D6**		

Package Labelling Compliance Comparison

When comparing package damage conditions with UN 38.3 testing non-compliances, packages with NC labelling have roughly equal chance of failing the UN 38.3 testing as the ones that passed. This suggests there is no correlation between improperly labelled packages and the likelihood of the LiB in the package failing UN 38.3.

Table 27: UN 38.3 Test non-compliances by compliant package labelling (Bold are failed sets)

Labelling	Sets		UN 38.3 NC	NC Rate
Compliant	A1 **A2** **A3** A5 **A6**	B3 B5 C1 **C2** D2	4 / 10	40%
Non-Compliant	**A4** B1 **B2** B4 B6 C3 **C4**	**C5** **C6** D1 D3 D4 D5 **D6**	6 / 14	43%

Transportation Mode Comparison

Batteries were procured using the fastest shipping method available which would potentially include transportation by aircraft. While only three sets could be confirmed to be shipped by air, it is concerning they not only failed the UN 38.3 testing but some of these sets (A4, B2) also had the most severe failures with fire and explosion events during testing. As noted previously, the A4 set created an explosion that was powerful enough to create a dent in the testing chamber. Further observations on these failures are found in Section 5.2. All sets travelling by air also failed to meet the 30% SOC requirement, which is independent to package labelling and UN 38.3 testing.

Table 28: UN 38.3 Test non-compliances by transportation mode (Failed sets in bold)

Mode	Sets		UN 38.3 NCs	Labelling NC Rate	SOC NC Rate
Air	**A4** **B2**	**C6**	3 / 3	100%	100%
Ground	A1 **A2** **A3** A5 **A6** B1 B3 B4 B5	**C2** C3 **C4** **C5** D1 D3 D4 D5 **D6**	7 / 18	39%	N/A
Unknown	B6 C1	D2	0 / 3	0%	N/A

OEM vs. Third-party Comparison

Results indicated only third-party replacement LiBs have failed UN 38.3 Test results [Table 29] so we can conclude that non-OEM third-party replacement batteries have a strong correlation to non-compliance with UN 38.3. This is concerning as unknowing consumers may purchase these batteries due to their significantly lower cost and often being advertised with a higher capacity than the OEM battery. This is supported when sorting the popularity/ranking of third-party replacement batteries purchased on marketplaces such as Market A.

Table 29: UN 38.3 OEM and third part non-compliances (Failed sets in bold)

Model	Sets		UN 38.3 NCs	NC Rate
OEM	A1 B1	C1 D1	0 / 4	0%
Third-party	**A2** **A3** **A4** A5 **A6** **B2** B3 B4 B5 B6	**C2** C3 **C4** **C5** C6 D2 D3 D4 D5 **D6**	10 / 20	50%

An interesting observation to note is when reading the labels across all the replacement batteries, there we observed several typos and misaligned text on the labels placed on third-party replacement batteries. This is further explored in Section 5.2. Also, it appears that the OEM batteries used cells manufactured in Korea and had their batteries assembled in China, while most of the third-party replacement LiBs were manufactured and assembled entirely in China.

LiB model type Comparison

All models had at least one failed third-party replacement set [Table 30]. This indicates substandard LiBs are not specific to one model of replacement batteries. For power tool models, it appears models A and C had more substandard LiBs than compared to model B. Two characteristics that were shared by models A and C were that they were more expensive than B, and they both had higher voltage than B.

When adding smartphones to this comparison (model D), it is likely that lower voltage correlates with lower rates of UN 38.3 failures, because model D had the lowest voltage and the lowest UN 38.3 NC rates.

Table 30: UN 38.3 Test non-compliances by model (Failed sets in bold)

Model	OEM Voltage	OEM Capacity	Sets		UN 38.3 NCs	NC Rate
A	20 V	6 Ah	A1 **A2** **A3**	**A4** A5 **A6**	4 / 6	67%
B	12 V	6 Ah	B1 **B2** B3	B4 B5 B6	1 / 6	17%
C	20 V	3 Ah	C1 **C2** C3	**C4** **C5** **C6**	4 / 6	67%
D	3.85 V	3.2 Ah	D1 D2 D3	D4 D5 **D6**	1 / 6	17%

Marketplace Comparison

Markets A, B, and C at least one failed set [Table 31]. Market C had the most non-compliant UN 38.3 test results with a non-compliance rate of 60%, followed by Market B with NC Rate of 56%, and Market A with an NC Rate of 33% when only considering third-party batteries. OEM batteries were removed for this comparison, because an equal number of OEM and non-OEM batteries was not purchased from each marketplace. Furthermore, due to having only one set tested for Market’s D and E, the NC rates for those markets are not statistically significant.

When looking at labelling NCs [Table 32], Market A was consistent in labelling compliance when shipping LiBs. Market C shipped at least one package in each set that was ordered with issues in labelling according to regulations [See Section 3.3]. This suggests some marketplaces may be better than others at following shipping and labelling requirements, however the labelling NCs do not show a significant relation to UN 38.3 NC rate. Having no labelling NCs can still result in both passing and failed sets (Market A), and having packages with labelling NCs (Market C, D, E) can also result in passing and failing sets.

Portable Rechargeable Battery Association suggested many of the worst abuses of substandard batteries originate in China [2]. This is difficult to find evidence for in this study, as almost all batteries were made in China regardless of marketplace and the origin of cells were not identified.

Table 31: Non-compliances by marketplace for non-OEM sets (Failed sets in bold)

Marketplace	Sets		UN 38.3 NCs*	UN 38.3 NC Rate*	Labelling NC
Market A	**A3** A5 B3	B5 **C2** D2	2 / 6	33%	0 / 6
Market B	**A2** **A6** **B2** B4 C3	**C4** **C5** D3 D4	5 / 9	56%	7 / 9
Market C	**A4** B6 **C6**	D5 **D6**	3 / 5	60%	5 / 5
Market D			-	-	-
Market E			-	-	-

* Excluding OEM batteries.

Table 32: Non-compliances by marketplace for OEM sets only

Marketplace	Sets		UN 38.3 NCs	UN 38.3 NC Rate	Labelling NC
Market A	A1	C1	0 / 2	0%	0 / 2
Market B	**-**		-	-	-
Market C	**-**		-	-	-
Market D	B1		0 / 1	0 %	1 / 1
Market E	D1		0 / 1	0 %	1 / 1

Shipper Comparison

When evaluating battery sets by the company that shipped the batteries, there does not seem to be any obvious trend with respect to likelihood of non-compliance with UN 38.3. While Courier C did not deliver any sets that failed the UN 38.3 tests, they only handled a small fraction of the packages. Unknown shippers did not provide a tracking ID to identify the shipping company used [Table 33].

Table 33: UN 38.3 Test non-compliances by shipper (Failed sets in bold)

Shipper	Sets		UN 38.3 NCs	NC Rate
Courier A	B1 **B2** **C6**	D1 D4	2 / 5	40%
Courier B	A1 **A2** **A3** A5 A6 B4	C1 **C2** **C4** **C5**	5 / 10	50%
Courier C	C3	D3	0 / 2	0%
Courier D	D5	**D6**	1 / 2	50%
Unknown	**A4** B3	B5 B6 D2	1 / 5	20 %

5.2 Trends in Severe UN 38.3 Non-Compliances (A4, B2, C2, C5)

Four sets of replacement batteries had what TC considers severe failures (fire and explosion). During UN 38.3 Testing, A4, B2, and C5 LiBs caught fire and exploded during the T.7 overcharge test. A4 and C2 also caught fire and exploded during the T.5 Short Circuit Test. Other failures such as the loss of voltage, loss of weight, high surface temperature, or leaked electrolyte are not considered to be severe NCs for the purpose of this study.

A4 was advertised as a higher capacity than the OEM (10Ah instead of 6Ah) and was also the lowest cost replacement battery procured in terms of price per unit. The battery was ordered through Market C, and the packages seem to have arrived by air. The battery itself has a label that states a capacity of 10Ah, though SOC testing found the actual capacity to be closer to 2.30–3.03 Ah. Also, the battery did not have any markings/warnings printed on the battery pack, while the OEM and other replacement batteries of the same equipment model did. Note that markings/warnings that appear on the battery itself is not related to the UN3480 battery label used for transport and are not subjected to any dangerous goods transportation related regulations.

During the charge and discharge stage prior to testing, one of the A4 batteries was found to have low voltage. The technician opened the battery case to find a broken weld which could be a potential reason for the multiple failures during UN 38.3 Testing [Figure 20], however further analysis would be required to determine the root cause.

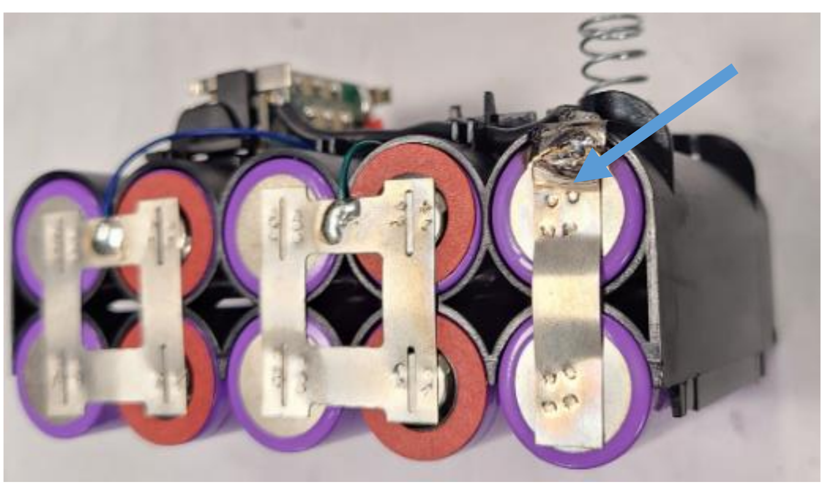


Figure 20: Broken weld found on untested A4 battery

B2 happened to have worldwide expedited shipping as an option, which made air shipment a more probable event if ordered. The battery was ordered through Market B and the packages seem to have arrived by air, based on the shipping label that had the code ORD – referencing the airport code for Chicago O'Hare International Airport. The markings on the battery pack have typos in the French and Spanish text.

C2 was sold through Market A and was selected as it was the lowest cost option on the storefront. On the battery pack, the word "CAUTION" was used instead of "warning" and seems to be misaligned with the rest of the text.

C5 was sold through Market B and was selected as a comparison point to C1. On the label on the battery pack, the text isn't using justified alignment rather than right aligned text and uses excessive capitalization through. The triangle beside the warning also does not have an exclamation mark typical of warnings. It should also be noted that although the C5 was advertised as a 20V 5.0Ah power tool battery, the discharge and charge stage measured the actual capacity of the battery to be 3.77 – 3.86 Ah.

Some characteristics common to the batteries that had severe UN 38.3 test failures are that:

I. All of these batteries were shipped with a SOC over 30%
II. A4, B2, and C5 had non-compliances with packaging requirements (incorrect or no label present)
III. All of these batteries had a lower mass than the OEM battery counterparts
    - A2 (579g) is lighter than the OEM A1 set (949g), same as B2 (380g) is to OEM B1 (426g), as well as C2 (357g) and C5 (613g) compared to OEM C1 (614g).
IV. All had markings on the battery that were either missing or had typos
V. A4 and B2 were shipped by air

Based on the analysis in Section 5.1, the characteristics noted above only correlate with those sets that had severe failures (fire and explosions), not necessarily with all batteries that failed UN38.3. tests.

There were only four sets with batteries that had severe NCs, so a larger sample size of NC sets would be needed to know if these characteristics truly correlate.

Out of the three sets that had packages shipped by air, all three of them had NCs. Two of which experienced fire and explosion events. A4 and B2 are of high importance as they were shipped without the proper labels, with batteries that had high SOCs, and had severe fire and explosion failures. As UN 38.3 Testing is meant to represent the environment and conditions LiBs could experience during shipping, these batteries pose a high hazard and high risk when transported by air, as they could lead to a serious incident on board an aircraft.

6.0 TEARDOWN ANALYSIS

In order to learn more about substandard batteries and why the batteries in this study failed UN 38.3 testing, TC had the National Research Council Canada (NRC) perform examinations and tests on new battery packs from sets A and B that were identical to those that failed the UN 38.3 tests as shown in Table 34. This work was broken into two major sections: battery examination and individual cell examination. Examinations were also performed on A1 and B1 OEM batteries for comparison. TC did not pursue testing for sets C and D after analysis and discussion on sets A and B suggested nominal benefit for additional testing.

Table 34: Battery Sets chosen for Battery and Cell Examination

Set ID	Charge/ Discharge	T.1	T.2	T.3	T.4	T.5	T.7	UN 38.3Test Result
Power Tool Batteries								
A1	✓	✓	✓	✓	✓	✓	✓	PASS
A2	✓	✓	✓	1 NC	✓	1 NC	✓	FAIL
A3	✓	✓	✓	3 NCs	✓	✓	✓	FAIL
A4	✓	✓	✓	✓	✓	5 NCs	7 NCs	FAIL
A6	✓	✓	✓	1 NC	✓	✓	✓	FAIL
B1	✓	✓	✓	✓	✓	✓	✓	PASS
B2	✓	✓	✓	✓	✓	✓	4 NCs	FAIL

✓ - All (Remaining) Batteries Compliant/Passing
NCs - Non-Compliances

6.1 Battery Examination

The type of examinations that were performed was based on which UN 38.3 tests the batteries in the set failed. The examinations included:

- General Battery Disassembly
- Cell Placement
- Battery Casing Mechanical and Thermal Properties
- Inspection of Connections and Wiring

In terms of overall construction, only small differences were observed between the batteries whether their design passed or failed UN 38.3 testing. All battery packs – excluding A4 – were covered in a plastic casing with similar tensile mechanical properties. There was little to no dust or debris present inside these batteries, no loose wires or parts were found, and the welding work had no issues.

The A1 OEM battery did exhibit additional safety features in the form of bare voltage sense wires (fusible links which can disconnect upon high temperature, overcurrent, or over-potential), current flow limiters, a secondary circuit board, and additional thermal paste and insulation. However, these features were not present in the B1 OEM battery or in any of the replacement battery sets, so it is not possible to gauge the impact of these additional safety features.

Set A4 did have some differences from the rest of the replacement batteries particularly in the welds. The welds looked like they were performed manually with significant quality and spacing variance in each weld. Some welds had minimal impact area, and one weld missed the tab [Figure 21] and had a large impact area.

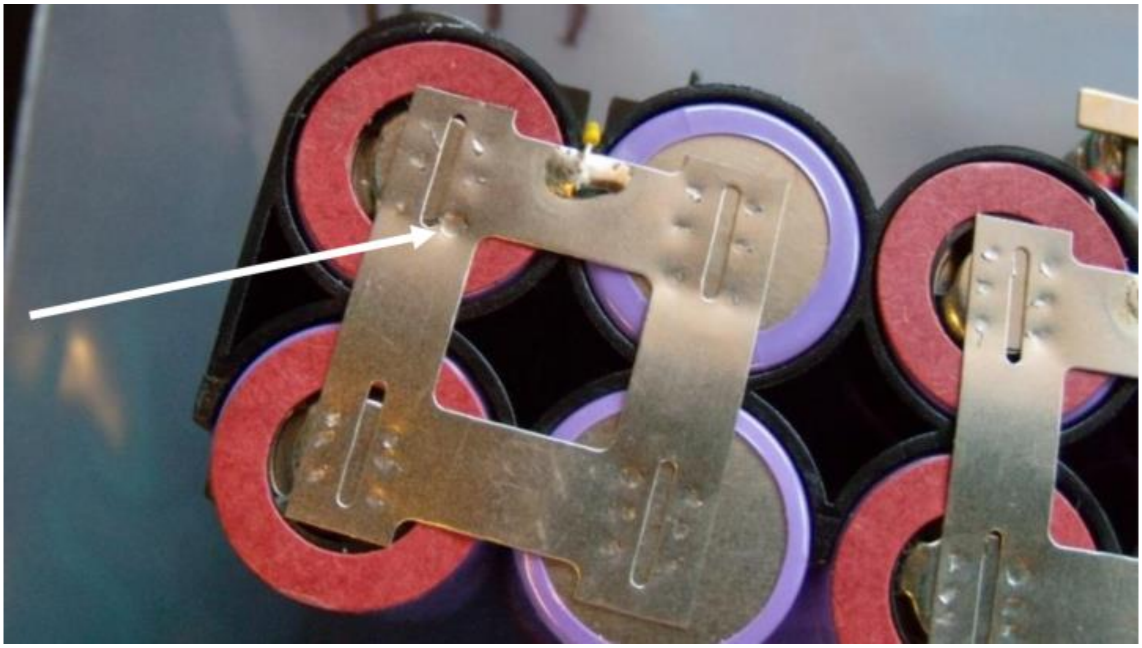


Figure 21: Missed weld on A4 battery

6.2 Cell Examination

The type of examinations that were performed was based on which UN 38.3 tests the batteries in the set failed. The examinations included:

- Micro CT Scan
- Dry room disassembly

Due to the lack of labels on the cells of A2, A4, and A6, it is possible that the cells which make up each battery are not from the same production cycle or even the same brand. It is best practice to use cells from the same production cycle to maintain pack balance and quality control. Having different cells may lead to cell imbalance and make them more susceptible to thermal runaway from cell overcharge or over discharge.

The micro CT Scan examined several details form one cell of one battery from each set in Table 34 including:

- Axial Offset Registry: The distance between the edges of the anode and the cathode
- Drift: Misalignments of the winding during manufacturing
- Shift: Misalignments of the winding due to mechanical abuse

Sets A4 and B2 had significantly misaligned electrodes resulting in little to no safety margin in the Axial Offset Registry [Figure 22, Figure 23]. This misalignment can lead to dendrite formation as the separator would not be able to stop ions from flowing, and eventually result in an exothermic runaway condition. In comparison, OEM sets A1 and B1 had minimal drift for their cells, and the other replacement sets (A2, A3, A4, A6) had some but still acceptable level of drift.

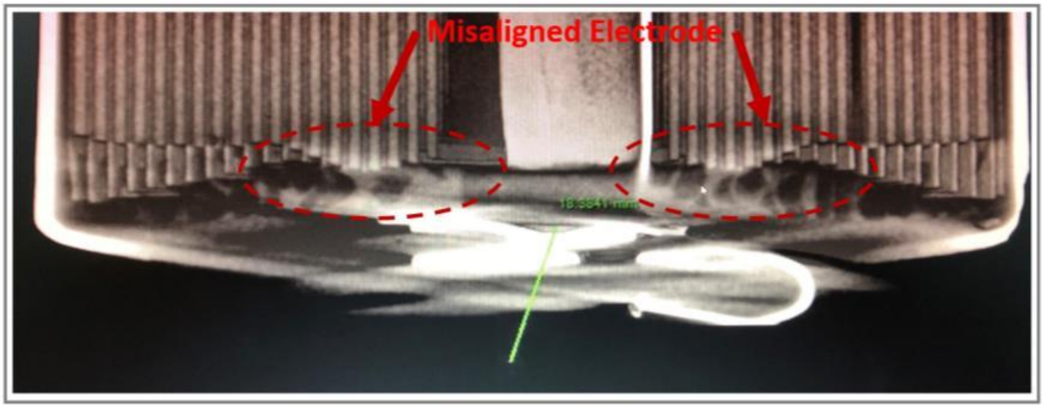


Figure 22: Set A4 cell – Misaligned electrodes

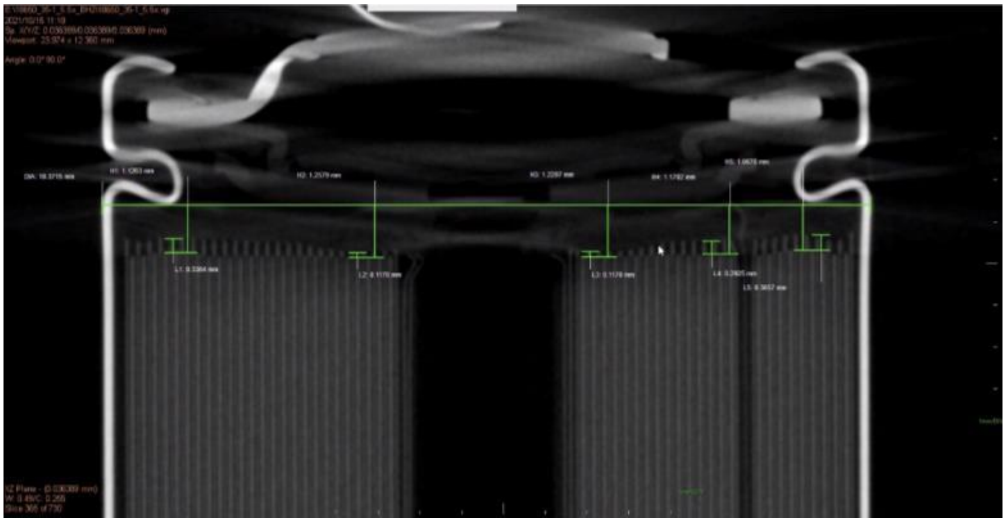


Figure 23: Set B2 - Misaligned electrodes

Misalignments can be due to the manufacturing stage from a bad wind, or post-manufacturing from manufacturing abuse. It is possible that cells from the third-party replacement batteries were either not produced by a company with an expected quality control and assurance system, or the cells were rejects or abused during the integration process. From NRC's experience, the small offset creates an extremely narrow margin for error on winding, especially when it comes to internal shifting/telescoping of the roll when mechanical abuse such as drop or vibration is applied.

For the cell from B2, the cell can was dented which could be evidence of mechanical abuse before or during installation.

For the cell from set A4, there is significant corrosion present, and the electrodes have the most delamination of the coating compared to other cells from Table 34 [Figure 24]. This again does not necessarily correlate to a fire and explosion during the UN 38.3 tests, but it can be a contributing cause.

The CT scan performed on substandard cells revealed that the reduced safety margin made them more prone to thermal runaway if they were physically abused (e.g., vibration, shock, crush). However, the exact amount of shift could not be determined from the scan, which would be determined by the actual abuse conditions experienced in the transportation cycle. Overall, NRC's cell examination shows deficiencies in cell construction present in some of the substandard batteries analyzed could be correlated with a higher probability of an incident than compared to OEM batteries.

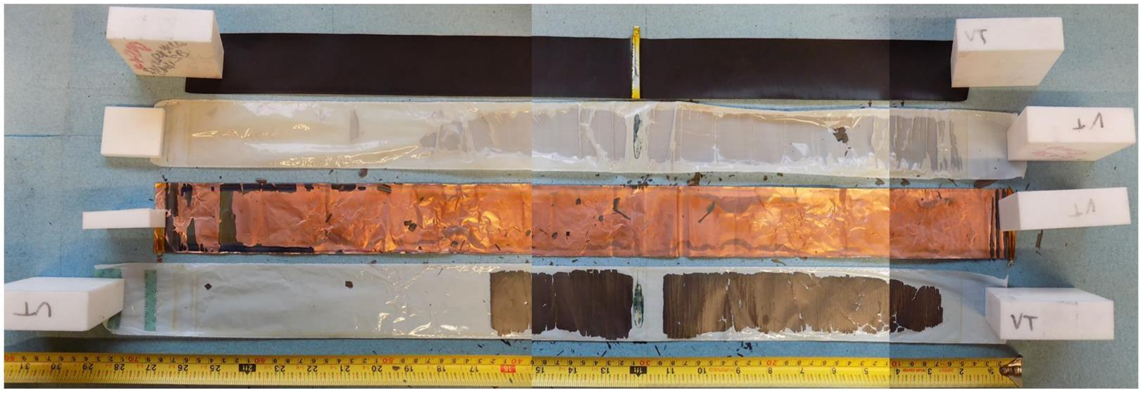


Figure 24: Set A4 - Corrosion and delamination present in disassembled cells

6.3 Thermal Runaway & Risk

A controlled thermal runaway following the RTCA DO 311A § 2.4.5.4 standard [16] was performed to evaluate the severity the thermal runaway characteristics of the LiB designs that failed UN38.3 testing as well as the OEM batteries (A1, A2, A3, A4, A6, B1, B2). While different sets initiated thermal runaway at slightly separate times, there were no other observed differences that would have resulted in a considerably different outcome between them. The resulting fire and explosion were similar for both OEM and substandard batteries.

If a risk analysis of power tool replacement battery shipments is performed, the severity of all the batteries seems to be the same (same hazard or consequence of failure), but substandard batteries will have an increased probability of failure due to increased likelihood of manufacturing deficiencies or post-manufacturing abuse which leads to a higher risk.

7.0 CONCLUSION

The aim of this study was to assess the hazards and risks substandard LiBs could be causing to the transportation system, as well as identify any shared features between substandard battery models that can help detect them during transport. This study shows that third-party replacement LiBs that do not pass UN 38.3 tests are entering the transportation system which have an increased risk over OEM batteries. Out of 24 LiB sets tested:

1. All four OEM sets had compliant UN 38.3 test results.
2. 10 out of 20 (50%) third-party sets recorded non-compliant UN 38.3 results. Another five third-party sets passed UN 38.3 testing but did have near-failures in certain tests that would have been flagged to the manufacturer by the test lab.
3. A third-party LiB with a higher voltage (e.g., 20V vs. 12V in this study) has a higher chance of having a UN38.3 NC than a third-party LiB with a lower voltage. The capacity of the LiB did not seem to have as significant of an impact as voltage did.
4. It was difficult to get UN 38.3 Test Summaries from sellers. Two sellers were not familiar with the test summary or explicitly stated they were unable to provide one. Only four summaries were received, but the reports for three of them did not seem to match with the LiBs shipped, and all four sets failed UN 38.3 when UL tested them.
5. 23 of 44 packages (52%) were missing the required labeling. 15 of the 44 packages were completely undeclared, including one OEM.
6. All three (3) sets that were shipped by air contained LiBs that failed UN 38.3 and were shipped at a SOC greater than the 30% allowed.
7. When comparing all sets, UN 38.3 non-compliances occurred regardless of package weight, handling, marketplace, seller, courier, packaging & labelling compliance, country of origin, and mode of transport
    - For sets that had severe failures during UN 38.3. tests (A4/B2/C2/C5), the substandard batteries were found to be cheaper and weighed less than their OEM counterparts, and also had typos and/or misaligned text on their labels.
8. Teardown analysis revealed deficiencies in the cells used in substandard third-party batteries correlated with a higher probability of an incident occurring than cells used in OEM batteries. With some minor exceptions, there were no notable differences in how batteries were constructed that would affect the hazard of the battery pack. The thermal runaway tests indicated that once the cell of a replacement battery was set into a thermal runaway, the resulting fire and explosion was similar for both passing and failing batteries. This means that the probability of an incident is the key element of controlling the risk, because the severity is generally the same.

To help address the safety risks identified by this study, Transport Canada is developing strategies to increase awareness and compliance with safety requirements. One strategy might be to provide guidance to help consumers, marketplaces, shippers, and regulators more readily identify batteries that might be non-compliant with UN 38.3 based on factors like low-cost high voltage products or battery labels with typos and increase awareness of the risks when purchasing third-party replacement batteries over their OEM counterparts.

REFERENCES

[1] United States Department of Transportation - Pipeline and Hazardous Materials Safety Administration, "Safety Alert - Transportation of Hoverboards (Lithium Battery Powered Vehicles)," [Online]. Available: https://www.phmsa.dot.gov/news/safety-alert-transportation-hoverboards-lithium-battery-powered-vehicles-0.

[2] P. R. B. Association, "PRBA Urges Crackdown on Non-Compliant Lithium Ion Battery Manufacturers in China," [Online]. Available: https://www.prba.org/general/prba-urges-crackdown-on-non-compliant-lithium-ion-Battery-manufacturers-in-china-1143/.

[3] UNECE, "UN Manual of Tests and Criteria Subsection 38.3, 6th Edition," [Online]. Available: https://www.unece.org/fileadmin/DAM/trans/danger/ST_SG_AC.10_11_Rev6_E_WEB_-With_corrections_from_Corr.1.pdf.

[4] "Top 10 e-commerce sites in Canada," Disfold, [Online]. Available: https://disfold.com/top-e-commerce-sites-canada/.

[5] webretailer, "The World's Top Online Marketplaces 2021," [Online]. Available: https://www.webretailer.com/b/online-marketplaces/#Top_online_marketplaces_by_country_and_region .

[6] Federal Aviation Administration, "Battery Incidient Chart," [Online]. Available: https://www.faa.gov/hazmat/resources/lithium_batteries/media/Battery_incident_chart.pdf.

[7] R. E. Lyon, R. N. Walters, S. Crowley and J. G. Quintiere, "Fire Hazards of Lithium Ion Batteries," [Online]. Available: https://www.fire.tc.faa.gov/pdf/systems/oct15meeting/lyon-1015-libs.pdf.

[8] PressureWashr, "Tool Industry Behemoths: The Tool Companies Who Make and Own Most Tool Brands," 28 June 2019. [Online]. Available: https://pressurewashr.com/tool-industry-behemoths/.

[9] ICAO, "Technical Instructions For The Safe Transport of Dangerous Goods by Air (Doc 9284)," [Online]. Available: https://www.icao.int/safety/dangerousgoods/pages/technical-instructions.aspx.

[10] C. Decès-Petit, K. Fatih and B. Zhang, "Lithium battery transport: assessment of the environmental conditions for lithium batteries shipping," National Research Council of Canada. Energy, Mining and Environment, 2019.

[11] UNECE, "UN Manual of Tests and Criteria," [Online]. Available: https://unece.org/fileadmin/DAM/trans/danger/publi/manual/Rev7/Manual_Rev7_E.pdf#page=428.

[12] Transport Canada, "Small Containers for Transport of Dangerous Goods, Classes 3, 4, 5, 6.1, 8, and 9,a Transport Canada Standard," October 2010. [Online]. Available: https://tc.canada.ca/sites/default/files/migrated/tp14850e.pdf.

[13] Office of the Federal Register, "eCFR :: 49 CFR Part 173 -- Shippers -- General Requirements for Shipments and Packagings," [Online]. Available: https://www.ecfr.gov/current/title-49/subtitle-B/chapter-I/subchapter-C/part-173.

[14] IATA, "Lithium Battery Guidance Document," [Online]. Available: https://www.iata.org/contentassets/05e6d8742b0047259bf3a700bc9d42b9/lithium-battery-guidance-document-2020.pdf.

[15] N. N. Hubert Biteau, "Transportation of Li-ion batteries: The State of Charge Parameter," [Online]. Available: https://www.nfpa.org/-/media/Files/News-and-Research/Resources/Research-Foundation/Symposia/2017-SUPDET/SUPDET17-Biteau---Nava.ashx.

[16] RTCA, "DO-311A - Minimum Operational Performance Standards for Rechargeable Lithium Batteries and Battery Systems," [Online]. Available: https://my.rtca.org/productdetails?id=a1B36000004iHaKEAU.