PHMSA Lithium Battery Packaging Evaluation

Final Report

PHMSA RFQ # 693JK319Q0007

Submitted To:
Mr. Rick Boyle
US Department of Transportation
Pipeline and Hazardous Materials Safety Administration
1200 New Jersey Avenue, SE
Washington, DC 20590

Submitted By:
Bob Richard
HazMat Safety Consulting, LLC
Phone: (773) 540-0837
Email: BRichard@hazmatsafety.com

Mike Pagel
HazMat Safety Consulting, LLC
Phone: (847) 971-8543
Email: Mpagel@hazmatsafety.com

INTRODUCTION

HazMat Safety Consulting (HSC), a dangerous goods consulting firm that specializes in the safe transport and storage of lithium batteries, conducted an evaluation of current lithium battery packaging practices for air transport. HSC gathered relevant information on how lithium batteries are shipped aboard aircraft through various methods, including direct interviews with cell/battery manufacturers and industry stakeholders, their own experiences working with clients in the sector, incident report research, review of applicable literature, and lithium battery packaging surveys deployed to trade associations. This report describes current industry packaging practices used for air transport of lithium batteries (UN3480 and UN3090), as well as recommendations on how to improve the safety of lithium batteries in air transport.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Lithium batteries are the primary electric storage technology used for mobile power applications, including consumer electronics, tools, electric vehicles, and medical devices. Lithium cells and batteries are the favored technology because they are reliable, energy dense, and affordable. However, under rare circumstances, lithium batteries fail, resulting in a reaction that may pose significant flame, heat, gas, and projectile hazards. This failure reaction is commonly referred to as “thermal runaway.” As a result of these potential hazards, there are strict regulations on the transport of lithium batteries by all modes. However, due to the unique potential for catastrophic incidents, the regulations are most stringent when transporting lithium batteries via aircraft.

The safe transport of lithium batteries is a high priority for the US Department of Transportation’s (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA). Along with the UN 38.3 lithium cell and battery tests, effective packaging is critical to prevent thermal runaway events that may result from short circuit, impact, vibration, or inadvertent movement of the batteries within the packaging. To better understand current packaging practices utilized by shippers for air transport of standalone lithium cells and batteries (UN3480 and UN3090), PHMSA commissioned HazMat Safety Consulting (HSC) to conduct a lithium battery packaging evaluation study. This report details the results of the study as well as recommendations to PHMSA regarding future regulatory and outreach initiatives.

HSC gathered information on current lithium battery packaging practices through: (1) direct interviews with representatives from various industries that manufacture, ship, and carry lithium batteries by air, (2) the results of surveys distributed to three trade associations involved in the battery space, (3) conducting research on industry packaging trends, and (4) a thorough review of available lithium battery incident data. The results are broken down by various sectors within the lithium battery space: cell manufacturers, pack assemblers, power tools, medical devices, and electric vehicles (automotive). Our research has indicated that most lithium cells and batteries shipped by air are contained inside fiberboard outer packagings, with some custom plastic or metal cases used for specialized battery packs.

The end goal of regulators is to enhance transportation safety. For lithium battery safety, risk reduction can be achieved not only through enhanced packaging, but also through the development, production, and incentivization of safer cells and batteries. HSC reviewed current regulatory and industry initiatives underway that aim to better understand lithium battery hazards, and what can be done to improve the safety of lithium cells and batteries in transportation. These efforts include the Society of Aerospace Engineers (SAE) G-27 Lithium Battery Packaging Performance Committee, the United Nations Working Group on Hazard-Based Classification of Lithium Batteries and Cells, as well as novel packaging and battery technologies that serve to minimize hazards associated with lithium battery thermal runaway events.

Finally, this report includes recommendations on how PHMSA can improve the safety of lithium batteries in air transport. HSC recommends that PHMSA clarify certain lithium battery packaging regulations, maintain temporary state of charge restrictions, continue their participation in interagency and industry battery safety efforts, improve data collection processes, encourage a multilayered safety approach, and consider alternative ways to assess lithium battery failure probability. Taken together, these recommendations provide PHMSA a roadmap on how to reasonably and effectively mitigate the risks associated with the transport of lithium batteries shipped as cargo aboard aircraft.

BACKGROUND

Lithium Batteries: Production, Uses, and Supply Chain

Lithium batteries are a widely used energy source for various types of products ranging from portable consumer electronics to electric vehicles. Lithium batteries have grown in popularity throughout the years because they are reliable, cost-effective, and very energy dense. These characteristics make lithium batteries attractive to product manufactures because, when compared to other battery types, they allow for extended battery life while reducing battery size/weight. The demand for lithium cells and batteries has been growing at a rapid pace. For example, the production of lithium ion cells jumped from approximately 3 billion cells produced in 2007 to over 7 billion produced in 2017.[1] As shown in Figure 1, demand was first driven by the surge in lithium battery-powered consumer electronics, but much of the current and projected future growth is likely to be driven by the widespread use of electric vehicles (EVs)[2].

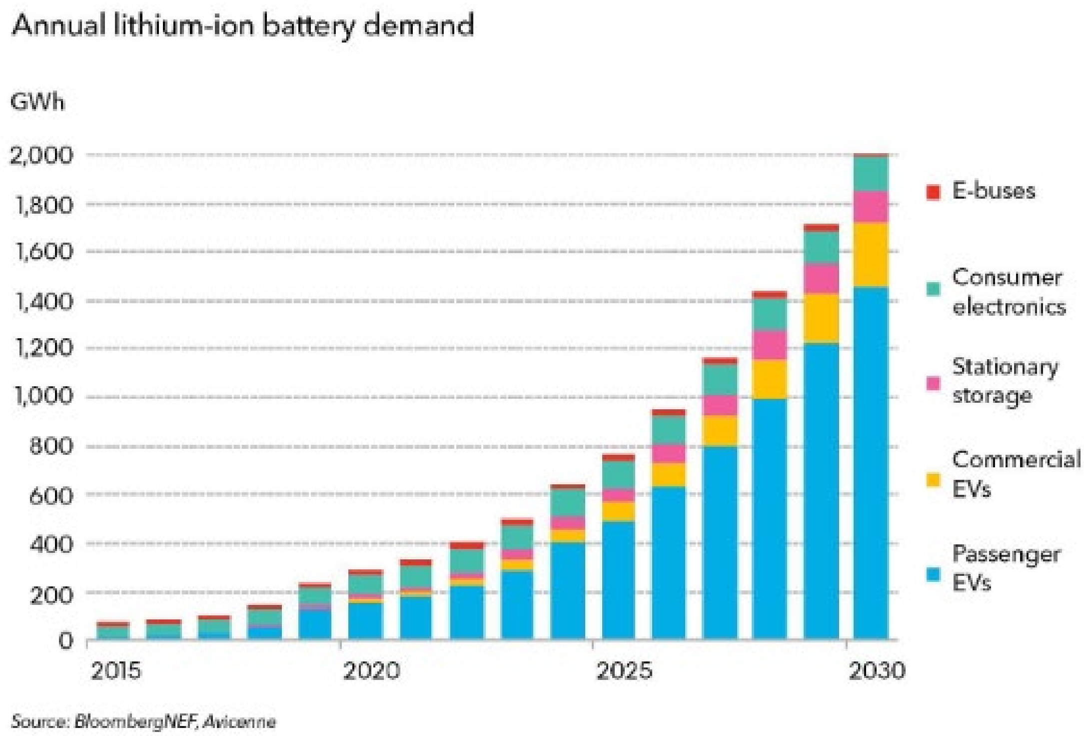

Figure 1

As manufacturers continue to produce enormous volumes of lithium cells and batteries to meet these demands, the safe transportation of cells and batteries within the supply chain is of utmost importance. While manufacturers of products powered by lithium cells and batteries are distributed across the globe, most lithium cells and batteries are produced in China.[3] Shipments of lithium cells and batteries originating in China are transported via all transport modes: highway, rail, ocean vessel, and air. With that said, the global distribution of lithium cell and battery purchasers in combination with the long delivery times associated with ocean vessel transportation make air transport a popular option for shipments originating in China and other Asian

---

[1] *Hazardous Materials: Enhanced Safety Provisions for Lithium Batteries Transported by Aircraft (FAA Reauthorization Act of 2018), 84 Federal Register 8010 (March 9, 2019).*

[2] *McKerracher, Colin. "Electric Vehicle Outlook 2019." Bloomberg New Energy Finance*

[3] *McKerracher, Colin. "Electric Vehicle Outlook 2019." Bloomberg New Energy Finance*

countries. Unfortunately, data on the volume of air shipments of lithium batteries are difficult to come by. According to a representative from the International Air Transport Association (IATA), the only accessible raw data is the number of air waybills, but the airlines do not collect the commodity data related to what was in the consignments.

To better understand commodity flow, HSC obtained data based on the Harmonized Tariff Schedule of the United States (HTS) related to air shipments of lithium batteries to and from the United States. Chapter 85 of the HTS covers electrical machinery and equipment and parts thereof including lithium cells and batteries. The HTS includes entries for primary (lithium metal) and secondary (lithium ion) cells and batteries. PRBA – The Rechargeable Battery Association – collects data on behalf of its members. The data on lithium ion and metal batteries for the last year the data was collected is as follows:

US Imports	Units (millions)	Shipments	Units per shipment	Kgs per shipment	Value per unit
Lithium Ion Batteries	69.3	56.0	1,239	204	$11
Lithium Metal Batteries	37.2	5.2	7,140	289	$3

US Exports	Units (millions)	Shipments	Units per shipment	Kgs per shipment	Value per unit
Lithium Ion Batteries	4.1	13.2	309	146	$70
Lithium Metal Batteries	5.6	7.1	786	101	$43

Figure 2

U.S. Air Trade Volumes for Affected Products (2018)

Once received by pack builders, product manufacturers, or other users, lithium cells and batteries are often integrated into products and offered for transport to customers – both business and consumer buyers. When it comes to second-order shipments of standalone batteries (including spare, replacement product batteries and power banks), the logistics often differ from those of the original cell manufacturer to the initial purchaser. For these shipments, air transport is not as common, which is a function of cost, compliance, and delivery expectations.

Over the previous five years, there have been significant restrictions imposed on air shipments of standalone lithium batteries in the International Civil Aviation Organization Technical Instructions on the Safe Transport of Dangerous Goods by Air (“ICAO Technical Instructions” or “ICAO TI”). These restrictions were incorporated into the US Hazardous Materials Regulations through the HM-224I rulemaking. The three most impactful are:

1. Beginning April 1, 2016, all standalone lithium ion cells and batteries must be shipped at a state of charge (SOC) not exceeding 30% of its rated capacity;
2. Beginning April 1, 2016, standalone lithium ion cells and batteries are prohibited from being shipped as cargo aboard passenger aircraft. A similar prohibition has been in place on standalone lithium metal cells and batteries since 2004 in the United States; and
3. Beginning in January 2017, major US air carriers UPS and FedEx instituted Operator Variations that prohibited their customers from offering small, standalone lithium cells and batteries in accordance with the Section II provisions of ICAO TI PI 965 and 968. Shippers were left to choose between the two more fully regulated options – Section IA and Section 1B.

Taken together, the three restrictions listed above have had major impacts to lithium battery supply chains. To start, managing the state of charge on a given cell or battery can be a complicated task – especially so for companies deeper in the supply chain that do not have direct connection with the original cell or battery manufacturer. Though some advanced battery packs have indicator lights or SOC displays, judging the SOC on most batteries and all cells is difficult. Compliance to SOC limits drives shippers away from utilizing air transport, as do the cargo aircraft restrictions. When batteries are prevented from being shipped aboard passenger aircraft, the supply of cargo space as well as regularly serviced destinations is reduced. Limiting available cargo space drives costs up for shippers – as do increasingly restrictive Operator Variations. In particular, the FedEx and UPS carrier variations (FX-05 and 5X-08, respectively) that prohibit their customers from utilizing Section II exceptions for small standalone lithium batteries have enormous impacts. With Section II, shippers are authorized to ship a single package containing no more than eight cells or two batteries. Provided they stay within these limitations and apply the appropriate marks to the package, no Class 9 lithium battery label nor shipping paper is required. This is a crucial point because most carriers assess hazmat surcharges to process packages that display a hazard class label and are accompanied by a shipping paper. With Section II, shippers can offer a few spare batteries to their customers without being charged a hazmat fee. By eliminating the Section II option, UPS and FedEx have pushed shippers to Section IA/IB, both of which require the Class 9 lithium battery label and shipping paper and, therefore, triggering the hazmat surcharge. Shipping costs for a package to which the hazmat surcharge applies may be five or ten times more expensive than a non-hazmat surcharge package. As a result, companies that previously offered replacement batteries to their customers via overnight air shipment have abandoned that service as it is cost prohibitive.

The industry-wide degree of withdrawal from air transport as a logistics channel for spare batteries is difficult to gather. Survey data collected as part of this project shows that nearly a third of companies that responded forgo air transport of spare batteries altogether. The reasons are varied but are likely tied directly to costs; costs associated with carrier hazmat fees, costs associated with additional employee training, and feared costs associated with financial penalties resulting from noncompliance. Some higher value commodities such as medical devices continue to utilize air transport based on the need to transport products expeditiously or because the alternative sea transport poses product quality issues because of challenges controlling environmental impacts (e.g. temperature extremes, saltwater exposure). HSC inquired with individual airlines and IATA to acquire data on the quantity of batteries transported by air, but unfortunately this is not data that the airlines collect or are capable of collecting. This issue is currently being addressed by members of the Lithium Battery Safety Advisory Committee mandated by section 333(d) of the FAA Reauthorization Act of 2018.

Combined with other factors, the withdrawal from air transport has altered the way that businesses ship lithium batteries. In the eCommerce realm, there is a demand for nearly instantaneous delivery. Instead of becoming reliant on air transport to meet this demand, eCommerce companies are optimizing their delivery methods by establishing strategically located distribution and fulfillment centers. In the past, large retailers operated regional distribution centers in the rural areas, feeding multiple physical retail stores within a specific state or region. Today, retailers operating eCommerce platforms must deliver direct to a widely geographically distributed customer base on tight timeframes, often aiming for two-day, one-day, and even same-day delivery. Instead of assuming these tight delivery windows would result in more air transport, eCommerce is leading to increases in LTL shipments, more strategically located fulfillment facilities, and the implementation of non-traditional delivery methods such as having contract workers make deliveries in rented vans or even their personal vehicles.

Current Air Transport Regulations for Lithium Batteries

For the purposes of dangerous goods regulations, there are six primary classifications for lithium batteries. As shown below, the six classifications are based on battery chemistry (e.g., lithium ion or lithium metal) as well as configuration (e.g., shipped by themselves (standalone), packed with equipment, or contained in equipment). The six classifications are:

- UN3480, Lithium Ion Batteries, Class 9
- UN3481, Lithium Ion Batteries Packed with Equipment, Class 9
- UN3481, Lithium Ion Batteries Contained in Equipment, Class 9
- UN3090, Lithium Metal Batteries, Class 9
- UN3091, Lithium Metal Batteries Packed with Equipment, Class 9
- UN3091, Lithium Metal Batteries Contained in Equipment, Class 9

In the United States, shipments of lithium batteries are subject to the transportation regulations promulgated by the Pipeline and Hazardous Materials Safety Administration (PHMSA). These regulations – mainly located in 49 CFR §173.185 – mandate certain packaging, hazard communication, and documentation depending on mode of transportation, as well as the type, battery chemistry, energy content, and quantity of batteries being transported. For air transport, shippers must also be aware of the international dangerous goods regulations developed by the International Civil Aviation Organization (ICAO). These regulations, the ICAO Technical Instructions for the Safe Transport of Dangerous Goods by Air, provide the specific requirements applicable to air shipments of lithium batteries (a summary table of applicable regulatory requirements is included in Appendix A). When US-based shippers offer packages to international destinations, they must adhere to the requirements of the ICAO TI or the IATA Dangerous Goods Regulations, which are a set of industry standards derived from the ICAO TI text. Further, though 49 CFR §173.185 dictates domestic regulatory requirements, many US air carriers demand their customers prepare all shipments in accordance with the ICAO TI requirements, as is allowable under the international authorization language of 49 CFR §171.22. Doing this is advantageous to carriers as it allows them to operate under a single, universal standard across the globe.

Fortunately, PHMSA consistently updates the Hazardous Materials Regulations (49 CFR Parts 100-185) to align with international standards, including the ICAO TI. The current requirements for air shipments of standalone lithium batteries (UN3480 and UN3090) differ based on cell/battery energy content and quantity. The primary regulations for air transport of lithium batteries are found in 49 CFR 173.185 as well as ICAO TI Packing Instructions 965 (UN3480) and 968 (UN3090). In both the 49 CFR and ICAO TI, there are three tiers, referred to in the ICAO TI Packing Instruction language as Section IA, Section IB, and Section II. Lithium batteries categorized as high-energy (e.g., lithium ion cells above 20 Wh, lithium ion batteries above 100 Wh, lithium metal cells above 1 g lithium content, and lithium metal batteries above 2 g lithium content) must be shipped in accordance with the Section IA requirements. For cells and batteries not exceeding the energy content thresholds previously listed – referred to as "small" cells and batteries – the shipper has the option of preparing packages in accordance with any of the three Sections, though most shippers adhere to Section IB or Section II due to the regulatory exceptions provided. As illustrated in Appendix A of this report, there is a great deal of complexity that shippers must navigate to make compliant air shipments of lithium batteries.

The current regulations regarding lithium battery packaging have two goals: 1) to prevent cells and batteries from short circuiting, and 2) to protect cells and batteries from sustaining damage in transportation enough to trigger a thermal runaway event. To accomplish these goals, regulators have imposed the following packaging conditions:

- ✓ Cells and batteries must be completely enclosed in non-metallic inner packagings;
- ✓ Cells and batteries must be separated from contact with equipment, other devices, or electrically conductive materials;

- ✓ Cells and batteries must be placed securely inside an authorized outer packaging in a manner to prevent movement of the cells/batteries that could cause damage; and
- ✓ Authorized outer packages include:
  - For lithium batteries eligible for the "small" (i.e. Section IB/Section II) exceptions, those inner packagings must be placed into a strong, rigid outer package capable of passing a 1.2 meter drop test without damage to the batteries, shifting of the contents to allow battery-to-battery contact, and release of contents.
  - For high-energy batteries (e.g., lithium ion batteries above 100 Wh), the inner packagings must then be placed into a UN Performance Package rated to the PG II performance level. Authorized packages are limited to:
    - Boxes: Metal (4A, 4B, 4N), wooden (4C1, 4C2, 4D, 4F), fiberboard (4G), or solid plastic (4H1, 4H2)
    - Drums: Metal (1A2, 1B2, 1N2), plywood (1D), fiber (1G), or plastic (1H2)
    - Jerricans: Metal (3A2, 3B2) or plastic (3H2)
  - Batteries that weigh 12 kg or more and are equipped with strong, impact-resistant outer cases may be excepted from UN Performance Package requirements in favor of strong outer packages, protective enclosures (e.g., crates), or securely strapped to pallets. For air transport, this is only allowed with prior Competent Authority Approval from PHMSA.

Confusion exists regarding what constitutes an inner packaging. As defined in 49 CFR §171.8, an inner packaging *means a packaging for which an outer packaging is required for transport. It does not include the inner receptacle of a composite packaging.* Based on the inner packaging language of 49 CFR §173.185(b)(3(i), plastic bags, blister packs, or retail cardboard display boxes would meet the requirement of completely enclosing cells/batteries in an inner packaging. However, some question whether dividers within a package would serve to meet the "completely enclosed by inner packaging" requirement if the cells or batteries rested on the top and bottom of the outer package itself. In this configuration, it does not seem to meet the requirement, though placing plastic/fiberboard top, bottom, and side wall layers around the dividers may meet the requirement. Given the varied configurations cell and battery shippers use for transport as confirmed through the information collected in this study, the inner packaging requirements are open to interpretation. In advance of the 57th session of the UN TDG Sub-Committee, the United States submitted a paper[4] proposing to add a requirement to UN Model Regulations Packing Instruction P903 that cells and batteries are to be completely enclosed in an inner packaging. This was meant as a harmonization measure to align UN Model Regulations text to the 49 CFR and ICAO TI requirements. Though the meeting has not been held, there is already significant opposition to this proposal among numerous Competent Authorities. While we are confident this issue will be resolved, this illustrates that lithium battery packaging requirements are subject to varying interpretations, not only among shippers, but among the regulators themselves.

Shippers must also comply with the applicable general packaging requirements of 49 CFR §173.24, §173.24a, and Part 4, Chapter 1 of the ICAO TI which includes use of sufficient cushioning material, secure package closure, and ensuring the packaging will withstand normal conditions of transport such as humidity, vibration, pressure, loading/unloading shocks, and temperature fluctuations. However, these requirements are somewhat subjective and different interpretations have led to incidents in transportation. For instance, we are aware of an incident involving the transport of recycled batteries that resulted in a fire because the batteries were not packed consistently with 49 CFR §173.24. In this case, the shipper did not intentionally violate the HMR, they merely did not understand the requirements and intent of the requirements.

---

[4] *ST/SG/AC.10/C.3/2020/56- (United States of America) Inner packagings for lithium cells and batteries – Clarification of requirements in Packing Instruction P903. 16 April 2020.*

As mentioned previously, there are also restrictions that apply to the air transport of standalone batteries, including state of charge limits on lithium ion cells and batteries (cannot exceed 30% of its rated capacity) and the prohibition on transporting standalone lithium batteries as cargo aboard passenger aircraft. According to ICAO, both measures were implemented on a temporary basis to enhance transportation safety. The SOC restriction is based on sound evidence that shows the hazards associated with lithium ion cell/battery thermal runaway are greatly diminished when the cell/battery is at a low SOC. The prohibition on transporting standalone lithium cells and batteries as cargo aboard passenger aircraft was implemented to reduce the likelihood of a catastrophic aviation incident involving lithium batteries.

The regulations also mandate employee training for those shipping lithium batteries aboard aircraft. For shippers of high energy cells and batteries, (e.g., lithium ion battery over 100 Wh), the full training requirements of 49 CFR Part 172, Subpart H apply. For small cells and batteries being shipped in accordance with Section II provisions, including those packed with or contained in equipment, the persons preparing shipments must receive “instruction” on the conditions and limitations applicable to these shipments (see 49 CFR §173.185(c)(4)(vii)). Though “instruction” is not defined in a detailed manner, shippers utilizing Section II provisions – the equivalent of 49 CFR §173.185(c)(4) text – are not subject to the full training requirements.

Though most shippers of Section II lithium cells and batteries packed with or contained in equipment adhere to the reduced training “instruction” requirement, shippers of small (e.g., lithium ion batteries not exceeding 100 Wh) standalone lithium cells and batteries by aircraft are generally pushed into the full training requirements because many air carriers will not accept Section II standalone cells and batteries. As a result, they are subject to the 49 CFR Part 172, Subpart H requirements as is made clear in 49 CFR §173.185(c)(5).

When lithium batteries were first introduced, PHMSA worked through the UN Transport of Dangerous Goods Sub-Committee (UN TDG Sub-Committee) to develop testing intended to classify cells and batteries and generally simulate worse case transport conditions to ensure safety. Lithium batteries must be able to pass each test stipulated in the UN Manual of Tests and Criteria, Part III, Section 38.3 (UN 38.3). These tests subject the battery or cell to a combination of significant environmental, mechanical, and electrical stresses designed to assess their ability to withstand the anticipated rigors incurred during transport. The tests include:

T1 – Altitude Simulation (Primary and Secondary Cells and Batteries)
This is low pressure testing that simulates unpressurized airplane space (cargo area) at an altitude of 15,000-meters. After storing batteries at 11.6kPa for 6 hours, these criteria shall be met: no mass loss, leaking, venting, disassembly, rupture or fire, and voltage within 10% of pre-test voltage.

T2 – Thermal Test (Primary and Secondary Cells and Batteries)
This test covers changes in temperature extremes from -40 °C to +75 °C. Batteries are stored for 6 hours at -40 °C (12 hours for large cells/batteries), then 6 hours at +75 °C (12 hours for large cells/batteries), for a total of 10 cycles. Testing may be performed in a single chamber or thermal shock chamber, but less than 30-minute transitions shall be used. To pass the test, there must be no mass loss, leaking, venting, disassembly, rupture or fire, and voltage within 10% of pre-test voltage.

T3 – Vibration (Primary and Secondary Cells and Batteries)
This test simulates vibration during transportation. The test is a sine sweep: 7Hz – 200Hz – 7Hz in 15 Minutes; 12 Sweeps (3 hours); 3 mutually perpendicular axes. For large batteries, the specifications change slightly. To pass the test, there must be no mass loss, leaking, venting, disassembly, rupture or fire, and voltage within 10% of pre-test voltage.

T4 – Shock (Primary and Secondary Cells and Batteries)
This test also simulates vibration during transportation. The test is a half-sine pulse: $150g_n$ for 6 milliseconds for small cells/batteries; $50g_n$ for 11 milliseconds for large cells/batteries; 3 pulses per direction; 6 directions. To pass the test, there must be no mass loss, leaking, venting, disassembly, rupture or fire, and voltage within 10% of pre-test voltage.

T5 – External Short Circuit (Primary and Secondary Cells and Batteries)
This test simulates an external short circuit of the cell or battery. At temperature of 57 ± 4 °C, apply short circuit (<0.1ohm) across terminals. Maintain at least an hour after sample temperature returns to 57 ± 4 °C. Pass criteria are that the case temperature does not exceed 170 °C and no disassembly, rupture, or fire within 6 hours of test.

T6 – Impact (Primary and Secondary Cells)
This test is only applicable to primary and secondary cells. For cylindrical, prismatic, or pouch cells, this test is meant to simulate impact to the surface of the cell. To pass the test, the external temperature does not exceed 170 °C and no disassembly, rupture, or fire within 6 hours of test.

T7 – Overcharge (Secondary Batteries)
This test is for secondary or rechargeable batteries only. It simulates an overcharge condition on a rechargeable battery. TO pass the test, there may be no disassembly or fire within 7 days after the test.

T8 – Forced Discharge (Primary and Secondary Cells)
This testing simulates a forced discharge condition for primary and secondary cells only. To pass the test, the external temperature does not exceed 170 °C and no disassembly or fire within 7 days after the test.

Over the years both PHMSA and the ICAO Dangerous Goods Panel have made incremental changes to the packaging requirements for lithium batteries to enhance safety. For instance, in HM-224F, PHMSA adopted amendments to the HMR to "include provisions to ensure all lithium batteries are packaged to reduce the possibility of damage that could lead to a catastrophic incident and minimize the consequences of an incident." ICAO has made several changes over the past 10 or more years to enhance lithium battery packaging including limiting the quantity of batteries authorized per package in the six applicable Packing Instructions (P965 - P970). The amendments were all intended to protect the batteries from damage, short circuit, and to ensure they are appropriately protected during normal conditions of transport. The current regulatory packaging requirements are based on the understanding that appropriately packaged lithium batteries are less likely to be subject to short circuit and damage. The packaging requirements recognize the importance of carefully preparing the inner packaging to prevent inadvertent movement and to prevent contact with other package contents, including metal objects that may cause damage or short circuiting in transport. Proper packaging is key to reducing risks associated with lithium batteries in transportation.

Lithium Battery Hazards

Much of the popularity of lithium batteries is due to their ability to store large quantities of energy in a small space. When functioning normally, a battery steadily releases energy to power a device. However, when batteries fail, the large stores of energy are released instantaneously, which may result in overheating, fire, overpressure, projectiles, and the generation of flammable and toxic gases. The common term to describe battery failure is "thermal runaway," which is described as "an irreversible exothermic chemical reaction within a cell causing an uncontrollable release of internal electrical and chemical energy resulting in a rapid and accelerating rise of temperature." Making matters more complicated, the hazards associated with a given cell or battery depend on a host of factors, including state of charge, cell chemistry, pack design, cell shape, energy content, and presence of any safety features. For example, a lower energy lithium coin cell may produce heat during a thermal runaway event, but the heat produced may not be enough to present an actual hazard in transportation. On the other hand, a poorly designed battery pack consisting of cylindrical cells can experience top, bottom, or sidewall rupture and will eject varying fractions of hot gas, liquid and vapor electrolyte, and solids, while retaining a portion of the generated heat within the cell, reaching incandescent temperatures. Thus, lithium battery reliability and safety are generally considered a function of the entirety of the cell, pack, system design, and manufacture.[5]

At present, dangerous goods regulations operate under the philosophy that higher energy batteries are more hazardous and, therefore, those cells and batteries are subject to more stringent packaging, hazard communication, and documentation requirements. This approach may change in the future as a result of the availability of battery failure data as well as the work of the UN Informal Working Group on Hazard-Based Classification of Lithium Batteries and Cells (more on this later in this report).

The fact that batteries can fail on rare occasions in an uncontrolled manner has brought an increased public awareness of battery safety, in particular as a result of some very large product recalls of portable notebook computer and cell phone batteries.[6] Both energetic and nonenergetic failures of lithium-ion cells and batteries can occur for a number of reasons, including:

a) poor cell design (electrochemical or mechanical);
b) cell manufacturing flaws;
c) external abuse of cells (thermal, mechanical, or electrical);
d) poor battery pack design or manufacture;
e) poor protection electronics design or manufacture; and
f) poor charger or system design or manufacture.

The hazards posed by lithium battery thermal runaway present a real threat to people and property in the supply chain. Nowhere is that threat more concerning than on an aircraft, where fuselages are not designed to withstand extreme fire and there is a lack of effective fire suppression systems. In its Interim Final Rule (HM-224I[7]), PHMSA highlighted that the FAA Technical Center issued a series of test reports in 2004, 2006, 2010, and 2014 that characterized the hazards posed by lithium cells and batteries transported as cargo on aircraft and the effectiveness of aircraft fire suppression agents, packagings, and packaging configurations. Specifically, the FAA Technical Center tested the ability of various fire extinguishing agents and fire resistant packagings to control fires involving lithium batteries. This testing revealed that:

---

[5] *Lithium-Ion Batteries Hazard and Use Assessment, Final Report, Celina Mikolajczak, PE, Michael Kahn, PhD, Kevin White, PhD, Richard Thomas Long, PE, Exponent Failure Analysis Associates, Inc, July 2011 Fire Protection Research Foundation*

[6] *For example, see: US Consumer Products Safety Commission, Alert #10-752, "Asurion Recalls Counterfeit BlackBerry®-Branded Batteries Due to Burn and Fire Hazards," August 10, 2010.*
US Consumer Products Safety Commission, Release #10-240, "HP Expands Recall of Notebook Computer Batteries Due to Fire Hazard," May 21, 2010.
US Consumer Products Safety Commission, Release #10-169, "Mobile Power Packs Recalled By Tumi Due to Fire Hazard," March 17, 2010.
Darlin D, "Dell Recalls Batteries Because of Fire Threat," The New York Times, August 14, 2006.
Kelley R, "Apple recalls 1.8 million laptop batteries," CNNMoney.com, August 24, 2006: 4:38 PM EDT.
US Consumer Products Safety Commission, Release #06-231, "Dell Announces Recall of Notebook Computer Batteries Due to Fire Hazard," August 15, 2006.

[7] *[Docket No. PHMSA–2016–0014 (HM–224I)] RIN 2137–AF20 Hazardous Materials: Enhanced Safety Provisions for Lithium Batteries Transported by Aircraft (FAA Reauthorization Act of 2018)*

(1) The ignition of the unburned flammable gases associated with a lithium cell or battery fire could lead to a catastrophic loss of the aircraft;
(2) The current design of the Halon 1301 fire suppression system in a Class C cargo compartment in passenger aircraft is incapable of preventing such an event; and
(3) The ignition of a mixture of flammable gases could produce an over pressure, which would dislodge pressure relief panels, allow leakage of Halon from the associated cargo compartment, and compromise the ability of fire suppression systems to function as intended. As a result, the smoke and fire can spread to adjacent compartments and potentially compromise the entire aircraft.

Moreover, the FAA testing concluded neither oxygen starvation through depressurization in the case of cargo aircraft nor common shipping containers (e.g., unit load devices) are effective in containing or suppressing a lithium cell or battery fire. Full-scale tests in a 727 aircraft demonstrated that, even in the presence of Halon 1301, cell-to-cell propagation occurred. The tests also demonstrated that the pressure and off gassing from the cells could reduce the Halon concentration at an accelerated rate, thereby causing the loss of fire protection earlier than designed. Recent testing showed that lithium-ion cells in thermal runaway emitted hydrogen gas that can be explosive even in a 5% Halon atmosphere. The ignition of the gases vented by a small number of cells in thermal runaway (the number depends on many factors, such as chemistry, design, and SOC of the cells, and size, design, and load factor of the compartment) can cause enough damage to a Class C cargo compartment as to render the Halon suppression system ineffective.[8] Regulators and industry experts agree that appropriate packaging plays a critical role in reducing both the likelihood of cells and batteries experiencing thermal events, as well as in reducing the hazards associated with cell-to-cell or battery-to-battery propagation.

In comments to PHMSA's rule, the Air Line Pilots Association (ALPA) stated that it does not believe that the Hazardous Materials Regulations (HMR) and ICAO TI requirements go far enough to address the safety risk created by lithium batteries. They have advocated that work must continue to develop and eventually mandate performance-based packaging standards that will prevent and/or contain a lithium battery fire. These standards must also address the threat from external fires.[9] In a White Paper[10] published in January 2016, ALPA recommended the following relative to packaging:

a) Continue work toward developing packaging that will prevent and/or contain a lithium battery fire.
b) Implement packaging restrictions and quantity limits for lithium batteries based upon the cargo compartment location and capabilities. This can be achieved by conducting testing on these batteries, fully charged, and packaged for transport, to determine the safe quantity of batteries that may be carried in Class C and E cargo compartments. Until testing is complete, adopt a conservative limit for the number of lithium batteries permitted in a single cargo compartment.

To address safety risks, an interim safety measure adopted by ICAO and codified in the HMR prohibits lithium ion batteries from being shipped at a SOC greater than 30% as cargo aboard aircraft. This SOC limit has been shown to:

a) halt or minimize the propagation of thermal runaway within a package;
b) Decrease heat release values with reduced states of charge;

---

[8] *DOT/FAA/TC-16/37 Federal Aviation Administration William J. Hughes Technical Center Aviation Research Division Atlantic City International Airport New Jersey 08405, Final Report Summary of FAA Studies Related to the Hazards Produced by Lithium Cells in Thermal Runaway in Aircraft Cargo Compartments, June 2016*
[9] *Safe Shipments of Hazardous Materials/Dangerous Goods Improving the Safety of Lithium Batteries Shipped by Air, http://www.alpa.org/advocacy/hazardous-materials*
[10] *ALPA White Paper Safely Transporting Lithium Batteries by Air January 2015*

c) Shipping cells at less than 50% state of charge may reduce the severity of a fire event;[11] and
d) The SOC affects the flammability limits in an apparent parabolic manner, where the widest flammability limits are at or near 100 % SOC.[12]

Initial testing found that most packaging did little to impede thermal runaway propagation from cell to cell and package to package when cells or batteries are offered for transport at 100% SOC. Lowering the SOC was shown to reduce the hazard. At 30% SOC, some cell chemistries stopped cell-to-cell propagation. By reducing the SOC of a typical lithium-ion cell to below 30%, the severity of thermal runaway is reduced, propagation of thermal runaway is slowed or eliminated, and the volume of flammable gases vented during thermal runaway is reduced.[13] While lowering the SOC is a proven way to minimize hazards of a thermal runaway, it should be noted that the probability of a thermal event in air transport involving new batteries is not a function of SOC.

The most conscientious cell manufacturers have reduced the incidence of internal cell failures but have been unable to eliminate them entirely. Cells manufactured under less stringent quality standards, and those damaged by usage or handling, pose an even greater threat. While the risk of thermal runaway can be mitigated by transporting cells at low SOC, assuring low SOC is not practical in all circumstances, such as returned consumer goods, those not discharged before transport, those where SOC is difficult to determine, and suppliers inadvertently shipping at high SOC.

Finally, it is vital to understand how current transportation and logistics operations affect lithium batteries in order to assess whether the extreme conditions that packages are subjected to during shipping will raise the risk of battery failures and increase the risk of a fire during the shipping cycle. Transport Canada recognized the need to better understand the shipping environment and commissioned the National Research Council Canada (NRC-CNRC) to conduct multiple studies to assess the environmental and mechanical stresses that packages are subjected to while they are being shipped around the world by different modes of transportation (ground, marine and air) [14, 15]. The study included an analysis of vibration levels, shock levels, humidity levels, and temperature fluctuations experienced. Also described were the extreme conditions that packages may be subjected to in transit and the human factors that affect their handling. The intent was to enable effective risk mitigation strategies for air shipments of products in various segments of the supply chain.

The most recent CNRC study tracked forty-four (44) packages to various international destinations. The results were:

a. When compared to ground shipments, packages containing lithium batteries moving via air experience a much lower number of shocks.
b. The peak temperatures experienced were -1.1 C (low) and 47.5 C (high), which are well within the test parameters defined in section 38.3 of the UN Manual of Tests and Criteria, which range from -40 °C to 72°C.

---

[11] *Summary of FAA Studies Related to the Hazards Produced by Lithium Cells in Thermal Runaway in Aircraft Cargo Compartments, DOT/FAA/TC 16/37, June 2016.*
[12] *Flammability Limits of Lithium-Ion Battery Thermal Runaway Vent Gas in Air and the Inerting Effects of Halon 1301, Matthew Eugene Karp, DOT/FAA/TC-TT16/55, September 2017, Rutgers University Graduate School, https://www.fire.tc.faa.gov/pdf/TC-TT16-55.pdf*
[13] *DOT/FAA/TC-16/37 Federal Aviation Administration William J. Hughes Technical Center Aviation Research Division Atlantic City International Airport New Jersey 08405, Final Report Summary of FAA Studies Related to the Hazards Produced by Lithium Cells in Thermal Runaway in Aircraft Cargo Compartments, June 2016*
[14] *Lithium Battery Transport Research Program Review of Environmental Conditions during Freight Transportation Cyrille Decès-Petit, Ph.D., Lei Zhang Ph. D., Manuel Hernandez, P.Eng., Khalid Fatih Ph.D., Mark Rossetto, P.Eng. and James Butler Ph.D. Prepared for: Transport Canada, October 11, 2016*
[15] *Lithium Battery Transport: Assessment of the Environmental Conditions for Lithium Batteries Shipping Cyrille Decès-Petit, Ph.D., Khalid Fatih Ph.D., Bryan Zhang Ph. D. Prepared for: Transport Canada, October 29, 2019*

c. The highest drop experienced was 1.38 m, which is above the 1.2m test associated with Section IB requirements as well as Packing Group II-rated UN Performance Packages. However, in 50% of shipments, the highest drops were less than 0.5 m.
d. The peak vibration energy experienced by packages was high. The authors noted it was difficult to compare vibration experienced in transport to the vibration tests of the UN Manual of Tests and Criteria because the vibration experienced in transport is random in nature, unlike the tests.
e. The top relative humidity (RH) some of the packages experienced (near 100% RH) was above the 50% or 65% RH that is required for preconditioning as part of the UN fiberboard packaging tests as described in 49 CFR §178.602. The report went on to cite concerns that long-term exposure (i.e., upwards of three weeks) may reduce the integrity of fiberboard packagings. While this is a concern for other modes, air shipments involving lithium batteries will likely be out of transportation well before a three-week period has elapsed.
f. The lowest pressure recorded was 778 kPa, which is above the 116 kPa threshold set by section 38.3 of the UN Manual of Tests and Criteria.

Due to the small sample size used in the study, it is difficult to draw concrete conclusions. Additional studies along these lines would be helpful in better understanding the typical environmental and handling extremes associated with air transport of lithium batteries. This may be particularly relevant and needed to assess eCommerce operations.

Lithium Battery Incidents in Transportation

PHMSA and FAA collect data on lithium battery incidents including fires aboard aircraft. PHMSA revised 49 CFR §171.15(b)(6) to require lithium battery incidents be reported based in part on a National Transportation Safety Board (NTSB) recommendation in their HM-215J Final Rule.[16] The NTSB recommendation stated:

> *NTSB Safety Recommendation A-07-107: Require commercial cargo and passenger operators to report to the Pipeline and Hazardous Materials Safety Administration all incidents involving primary and secondary lithium batteries, including those contained in or packed with equipment, that occur either on board or during loading or unloading operations and retain the failed items for evaluation purposes.*
>
> §171.15(b)(6) requires that *"During transportation by aircraft, a fire, violent rupture, explosion or dangerous evolution of heat (i.e., an amount of heat sufficient to be dangerous to packaging or personal safety to include charring of packaging, melting of packaging, scorching of packaging, or other evidence) occurs as a direct result of a battery or battery-powered device."*

There have been several incidences of lithium battery failure during air transport. In the HM-224F Notice of Proposed Rulemaking PHMSA stated that "most of the lithium battery incidents have been determined to originate from packages in non-compliant shipments of lithium batteries." However, there have been incidents involving lithium batteries packaged and offered for transport in compliance with applicable regulations. In most cases it is not possible to assess if the reported incidents were the result of damage that occurred during transportation and whether the packaging was deficient, or even possibly played a role as a causal factor in the incident. It is important to note that when an incident occurs involving a lithium battery or battery powered product, one of the most important data points to understand is whether the battery is from the original equipment manufacturer (OEM). That is, was the battery abused or tampered with, and in the case of a product, was the battery that came with the product involved in the incident or was it replaced by a repair facility, consumer, or some other third party? There are do-it-yourself (DIY) and right-to-repair websites instructing consumers on how to replace embedded lithium ion batteries.

More recently the NTSB highlighted packaging deficiencies and non-compliance as a cause of incidents. In their latest Safety Recommendation Report[17], NTSB stated:

> "The NTSB previously investigated an accident involving a prototype lithium-ion battery that was transported under the special permit process. On August 7, 2004, a battery caught fire while inside a unit load device (ULD) just prior to being loaded onto a FedEx airplane in Memphis, Tennessee. Loading personnel noticed the smoke from the ULD as it was about to be pushed into the cargo area of the airplane. Personnel returned the smoking ULD to the ground and called emergency responders, who then tried to open the ULD; a fire then ignited, destroying the ULD. Estimated damages were $20,000. The NTSB determined that the probable cause of the fire was "the failure of the unapproved packaging … which was inadequate to protect the lithium-ion battery modules from short circuits during transportation."

[16] *Hazardous Materials: Revision to Requirements for the Transportation of Batteries and Battery-Powered Devices; and Harmonization with the United Nations Recommendations, International Maritime Dangerous Goods Code, and International Civil Aviation Organization's Technical Instructions, 74 Federal Register 2203 (January 14, 2009).*
[17] *National Transportation Safety Board Washington, DC 20594, Safety Recommendation Report Standards for Lithium-Ion Battery Shipments by Air, May 28, 2020*

Appropriate packaging can reduce the probability of a single cell thermal event or cell-to-cell or battery-to-battery propagation, thereby reducing the overall hazard when a cell or battery in a package containing multiple cells or batteries experiences a thermal event. There have been incidents where the damage that induced the thermal runaway occurred during transportation (e.g. the battery or device containing the battery was dropped or hit with large equipment). The packaging needs to provide enough protection when the package is dropped.

PHMSA collects lithium battery incident data and attempts to identify root causes, though this proves challenging for several reasons:

a) Evidence is in many cases destroyed;
b) PHMSA is not always able to access the damaged products;
c) Failure of person in possession to report the incident;
d) Failure to follow up on the part of investigators; and
e) Unwillingness of industry to share failure causal data due to litigation and corporate image reasons.

The Lithium Battery Safety Advisory Committee has accepted the task of reviewing data collection and analysis with a focus on:

- Review of current incident data collection methods (e.g. Hazmatics);
- Root cause analysis and follow up investigation;
- Mandatory vs. voluntary reporting; and
- Understanding undeclared vs. misdeclared.[18]

PHMSA has a publicly searchable incident report database which, among other things, provides data on the shipper, carrier, result of the incident, and – in some cases –type of packaging used. PHMSA regulations require that the person in possession of the material at the time of the incident must submit an incident report form (5800.1 form) to the agency. For lithium batteries specifically, the person must report when an undeclared package is discovered or there is a fire, violent rupture, explosion or dangerous evolution of heat as a direct result of a battery or battery-powered device. A review and analysis of PHMSA's incident report data on air shipments of standalone lithium metal and lithium ion batteries reveals the following trends:

Incidents involving UN3480, Lithium ion batteries

- There were 283 reported incidents involving air transportation of standalone lithium ion batteries ranging from September 3rd, 2010 through March 22nd, 2020.
- Of the 283 reported incidents, 227 (80%) involved lithium batteries being transported as cargo. The 56 incidents involving passenger checked or carry-on bags as well as in-cabin incidents were removed from the list as they are outside the scope of this study. Those incidents are tracked in more detail by the FAA (see https://lessonslearned.faa.gov/UPS6/battery_incident_chart.pdf).
- Of the 227 reported incidents, 32 (14%) were incidents that resulted in overheating, fire, or the emission of gases. The other 195 reports, making up 86% of the total, were reports of likely undeclared packages containing lithium batteries.
- Of those 32 incidents, 29 were in fiberboard outer boxes (94%), with two incidents involving batteries in plastic bags and one incident where packaging was unreported.
- Of the 227 reported incidents, 205 had a reported package type. Of the 205, 161 (79%) were fiberboard boxes, 30 (15%) were plastic bags/boxes, and the rest included metal, plywood, textile, and paper boxes.

---

[18] *Lithium Battery Air Safety Meeting Minutes January 22-23, 2020,* *https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/docs/standards-rulemaking/hazmat/73431/signed-lbcminutesjan22-2320.pdf*

- Of all incidents reported, no injuries or fatalities were recorded.

Incidents involving UN3090, Lithium metal batteries

- There were 180 reported incidents involving air transportation of standalone lithium metal batteries ranging from September 26th, 1996 through February 21st, 2020.
- Of the 180 reported incidents, 169 (94%) involved lithium batteries being transported as cargo. The 11 incidents involving passenger checked or carry-on bags as well as in-cabin incidents were removed from the list as they are outside the scope of this study. Those incidents are tracked in more full detail by the FAA.
- Of the 169 reported incidents, 36 (21%) were incidents that resulted in overheating, fire, or the emission of gases. The other 133 reports, making up 79% of the total, were likely reports of undeclared packages containing lithium batteries.
- Of those 36 incidents, 23 were in fiberboard boxes (64%), with six incidents involving batteries in plastic bags and seven incidents where packaging was unreported.
- Of the 169 reported incidents, 144 had a reported package type. Of the 144, 113 (78%) were fiberboard boxes, 21 (15%) were plastic bags/boxes, and the rest included metal, textile, and paper boxes.
- Of all incidents reported, no injuries or fatalities were recorded.

CURRENT PACKAGING PRACTICES

Data Collection Methodology

HSC conducted interviews with companies involved in the lithium battery industry to get a better understanding of current packaging practices. The list below details the sectors of the industry that were interviewed as part of this study. The findings from these interviews are described in this section of the report.

- Major producer of power tools
- Major battery pack manufacturer
- Major cell manufacturer
- Medical device battery producer
- Producer of electric vehicles (automotive)

In addition, HSC developed surveys to gather relevant information on packaging practices for shippers of lithium batteries. The surveys asked participants whether their company ships lithium batteries by aircraft, what types of batteries they ship (e.g. "small" and "large-format"), the battery sector they operate in, the types of inner/outer packagings used, packaging sources, and any packaging best practices or new technologies used by their company. The surveys were sent to the member of the following trade associations:

- Council on Safe Transportation of Hazardous Articles (COSTHA)
- PRBA – The Rechargeable Battery Association
- The Medical Device Battery Transport Council (MDBTC)

The survey responses provided insight into how a variety of battery shippers package and ship lithium batteries for air transport. Findings from the survey results and interviews are described in this section of the report.

Cell Manufacturers

The quantity of lithium cells shipped for purposes of individual use or for pack assembly is significantly large, especially to support the power tool and automotive industries. Most lithium cells are produced in China, Japan, and Republic of Korea and are shipped to customers around the globe. Due to the restrictions on UN3480 and UN3090 for air transport (e.g. 30% SOC, passenger aircraft prohibitions), cell suppliers have undergone a major supply chain upheaval in recent years to get many of their cells from Asia-Pacific suppliers to the United States by ocean vessel. Still, air transport is used by cell manufacturers.

Cell manufacturers do not utilize Section II provisions to ship lithium cells because many carriers do not accept these shipments and, even if they did, the maximum quantities authorized (two batteries or eight cells per package and one package per consignment) are far too limited to be practical. Instead, cell manufacturers use either Section IB or Section IA provisions, with the key differences being that Section IB has reduced net weight limits and does not require UN-rated packaging. In many cases, bulk purchasers of lithium cells (i.e., pack manufacturers) can influence how cells are packaged for transport and typically mandate specific packaging primarily for quality purposes.

Based on interviews and survey results, there are multiple configurations used as inner packagings for cells. Unlike batteries, most cell manufacturers will not individually enclose cells in an inner packaging. Instead, they will place multiple cells inside a single inner packaging, which is acceptable because each cell is enclosed by an inner packaging. Egg crate designs where cells are nested into individual compartments are a common configuration used to ship cylindrical cells, including both lithium metal and lithium ion chemistry (Figure 3). In this configuration, terminals are protected from contact with one another by the layer of material (typically cardboard or foam) immediately below and above the cells. This design serves to completely enclose cells and prevent movement of cells within the outer packaging. As seen in Figure 4, there are also shippers only using fiberboard dividers to meet inner packaging requirements. Another type of cell, lithium metal button cells, are commonly shipped in trays – either cardboard or molded plastic – with divots that fit individual coin cells (Figure 5). Like the egg crate design, this serves to protect against short circuit and prevent cells from moving during transport. The trays are then stacked into outer packagings with cardboard liners and plastic sheeting separating each layer. Because they are so small, one button cell manufacturer indicated that a single package may contain hundreds or even thousands of button cells without exceeding the Section IA net weight limit of 35 kg.

Figure 3
Cylindrical lithium ion cells in egg crate configuration

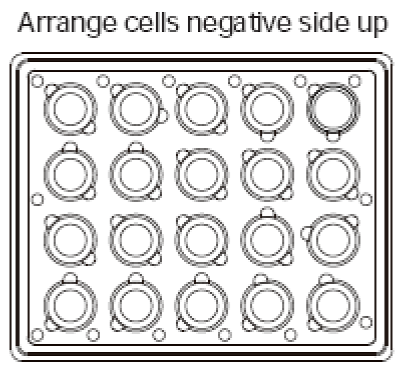

Figure 5
Drawing of plastic tray for lithium metal button cells

Figure 4
Cylindrical lithium ion cells in 4G box with dividers

Outer packagings used by cell shippers are overwhelmingly fiberboard boxes. For Section IB shipments, these are strong, rigid outer fiberboard boxes capable of passing the 1.2-meter drop test. For Section IA shipments, which are more frequent for high-volume cell shippers, the outer packaging is a UN 4G fiberboard box rated to either Packing Group I or II. Based on our research, there is a mix between companies that self-certify their own custom packaging to the UN Performance Standards and those that source these packages from third-party suppliers.

Electric Vehicles (Automotive)

Batteries used to power electric vehicles are lithium ion chemistry with Watt-hour ratings measured in terms of kilowatt-hours (kWh) – making them at the upper end of energy content of lithium ion batteries. The fully assembled battery pack often consists of multiple modules, with each module containing hundreds of lithium ion cells (some manufacturers use prismatic cells and others use cylindrical). Though lithium ion batteries are extremely energy dense, to store kilowatt-hours of energy the battery has rather large dimensions and weighs several hundred kilograms. To ship a standalone lithium ion battery exceeding 35 kg aboard an aircraft, the shipper must gain approval from the Competent Authority of the country of origin as is required by 49 CFR 172.102 Special Provision A54 and ICAO TI Special Provision A99. This can be a time-consuming process and, even if granted approval, many air carriers are uncomfortable with large format lithium ion batteries and refuse to transport them. As a result, many automotive producers limit the frequency of air transport of their battery packs and modules. However, two-thirds of respondents in the electric vehicle space indicated they do make air shipments of either their fully assembled packs or modules under rare, business-critical circumstances.

Accepting that most automotive battery packs and modules weigh more than 35 kg, alternative packaging to what is required in 49 CFR §173.185 is typically applied under the terms of the Competent Authority Approval. Due to the large dimensions, inner packagings (e.g., plastic bag) that completely enclose the battery are often not practical. Instead, shippers cover terminals using terminal caps or the terminals are recessed and covered with tape or other non-conductive material. Beyond terminal protection, many companies utilize complex battery management systems (BMS) within their batteries that monitor for abnormal internal conditions. Should such a condition occur, the BMS is able to shut down power to the battery to prevent abnormal conditions from triggering a thermal runaway reaction.

Per 49 CFR §173.185(b)(5), lithium batteries that exceed 12 kg are excepted from UN Performance Packaging if they have a strong, impact-resistant outer casing. Instead of UN-rated packaging, the batteries may be transported in protective enclosures (e.g., wood crates) or directly mounted to pallets or other handling devices. Like batteries that exceed 35 kg, shippers must gain Competent Authority Approval to be authorized to use this exception for transport aboard cargo aircraft. Whether using UN-rated packaging or a protective enclosure (see Figure 6 for examples), the heavy weights and odd dimensions often push automotive battery shippers to use custom packaging. Based on survey results, the custom cases may be wood, plastic, or metal and are often lined with fire-resistant foam and other robust packaging materials to keep batteries stabile during transit. Though these custom packagings are often expensive, automotive battery shippers can justify these costs because the packages are reusable (often shipping in closed loop supply chain) and the batteries themselves are so valuable that their protection during transport is the overriding priority.

Figure 6

Power Tools

Where power tools were once using other battery types (e.g., Nickel Cadmium or Nickel Metal Hydride) as their power sources, the industry has since moved overwhelmingly in the direction of lithium battery technology. Lithium batteries are used to power various types of cordless tools, including screwdrivers, leaf blowers, weed-whackers, chainsaws, hammer drills, and circular saws. The energy content of the lithium battery varies based on the application but, with a few exceptions, mobile power tools are using rechargeable lithium ion batteries.

Most of the lithium ion battery packs are composed of cylindrical lithium ion cells. The cells or assembled packs are often shipped from overseas suppliers via air to power tool manufacturers. Once on-site, cells are assembled into battery packs, tested to UN 38.3 standards, and integrated into the product for shipment. For direct-to-retail shipments, most products are shipped with the battery installed in equipment (UN3481, Lithium ion batteries contained in equipment) or with one or two spare batteries packed alongside the equipment in a toolkit (UN3481, Lithium ion batteries packed with equipment). Power tool suppliers do sell spare batteries to retailers or direct to consumer, but those shipments are typically made using ground transport. One respondent indicated that only 3% of their spare battery shipments were made using aircraft.

When standalone lithium batteries are shipped via air, respondents reported that they individually enclose battery packs in inner packagings, specifically in plastic bags or in the plastic blister pack used for display in retail settings (see Figure 7). The inner packaging requirement is a means to prevent short circuit. However, power tool batteries are a bit different than other battery packs in that they are often designed to be easily removed from the device to facilitate swapping a charged battery for an uncharged one. As a result of this operational reality, the battery packs have recessed terminals to prevent short circuit and terminal connection. In our conversations, one power tool manufacturer questioned the need for inner packagings that fully enclose the battery pack because it is nearly impossible to short out their battery based on the design. Further, they considered whether an exception from complete enclosure would be justified if the pack design is such that a short circuit is impossible because the terminals cannot be bridged. They proposed such an exception would be based on the successful testing of the Probing Test of IEC 60529, which tests whether a foreign object can get into vent or other openings that would result in a short circuit. This type of exception may reduce regulatory burden and packaging waste without reducing transportation safety.

For lower energy batteries being shipped in accordance with Section IB, inner packagings containing batteries are then typically shipped in fiberboard boxes with bubble wrap used as cushioning material to prevent movement within the package. According to respondents, these companies perform the 1.2-meter drop test on their boxes to ensure their integrity. Further, one respondent said they are increasingly certifying their packages to meet certain standards of the International Safe Transit Association (ISTA), specifically ISTA 1A, 3A, and 6A. This respondent reported that they are moving toward adherence to these standards to ensure safe shipments and because certain eCommerce partners are pushing them in this direction. Though none of the standards are specific to lithium battery packaging, they are general packaging integrity tests designed to show the package and product are capable of withstanding normal transport conditions.

Figure 7

Battery Pack Manufacturers

Pack assemblers purchase lithium ion cells from cell suppliers. While the technology was first researched and invented in the United States, most cells are produced in Asia. The majority of cell suppliers are based in China (e.g. CATL, Lishen, BYD), Japan (e.g. Panasonic) and Republic of Korea (e.g. Samsung, LG Chem). Figure 8 shows the import/export flow of lithium ion cells from 2014. There have been several initiatives to manufacture cells in the United States, but most of the volume (estimated at 88% in 2017) continues to be sourced from Asia.[19] Pack assemblers build battery packs for their customers for all types of applications. In our conversations with pack manufacturers, most packs are rechargeable lithium ion batteries. However, there are lithium metal packs used in oil and gas exploration, black boxes, and other applications where recharging is impractical. The energy content of packs differs based on application. Many pack manufacturers build "small" packs for portable consumer electronics devices as well as large format packs for more energy-consumptive applications like mobility aids, tools, and vehicles.

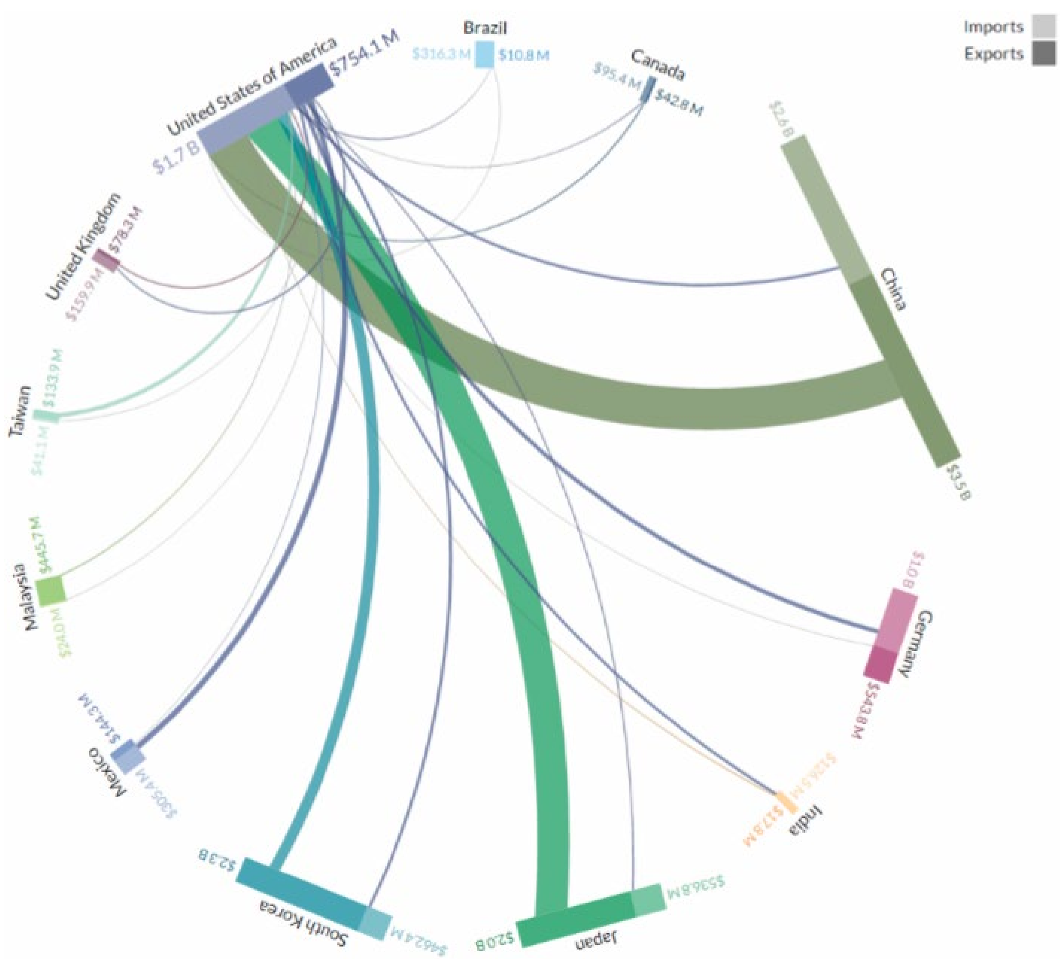

Figure 8

Import / Export of Lithium Ion Cells, 2014 (Debra Sandor, January 2017)

---

[19] *Breaking Down the Lithium-Ion Cell Manufacturing Supply Chain in the U.S. to Identify Key Barriers to Growth. Chris Dougher and Timothy L. Johnson, Ph.D., Advisor, Duke University, April 23rd, 2018*

Survey results, as well as interviews, have revealed that most pack manufacturers individually enclose battery packs and do not place multiple packs inside of one inner package. Terminal covers are used in some circumstances, though in other cases the shipper deems them unnecessary because terminal protection is built into the design of the pack itself. The inner packaging reportedly used includes anti-static plastic bags (see Figure 9 below), blister packs, and retail-ready fiberboard cartons. Reported cushioning materials included bubble wrap, heavy kraft paper, foam liners, packing peanuts, and, in one case, a fire-resistant foam that is intended to contain some of the hazards associated with a thermal runaway event. The shipper using this foam indicated it is of high-performance, lightweight, and relatively thin. They use it provide an extra level of safety and to give them “some added peace of mind” for their relatively infrequent air shipments. However, they also acknowledged that widespread use of the material for high volume air shippers would not be financially feasible due to the costs of the material. The same shipper reported that packing peanuts were the least effective of all options given that they did little to stabilize the batteries inside the box and the package recipients found the peanuts to be a mess.

One respondent reported confusion about inner packaging requirements, particularly regarding the circumstances under which the battery case itself may be considered the inner packaging. As a matter of regulation, the battery case is part of the article and, therefore, cannot be considered the inner packaging – even if the terminals are recessed or otherwise protected. Per 49 CFR 173.185(b)(3(i), that battery pack must be placed into an enclosure that is separate from the battery case and outer package.

Fiberboard boxes are the primary outer packages reportedly used by battery pack manufacturers. Based on the energy content of the battery, the packages will either be strong, rigid, non-UN-rated fiberboard boxes adhering to Section IB packaging requirements or UN 4G boxes for Section IA batteries. For their non-specification boxes, one respondent shared that they source boxes with an Edge Crust Test (ECT) specification of 32 lbs./inch for smaller batteries and one with an ECT rating of 48 lbs./inch for larger batteries. In their years of shipping batteries by both ground and air transport, they have not experienced issues regarding packages not withstanding normal conditions of transport.

Figure 9
Large format lithium ion battery in a plastic inner bag placed in 4G fiberboard box with foam inserts for stability.

Medical Device Batteries

Lithium cells and batteries that power medical devices[20] are typically categorized as "small" lithium batteries, though some implantable devices and high-power devices (e.g., defibrillators) are powered by lithium metal cells and batteries that exceed 1 or 2 grams of lithium, respectively. Due to critical public health needs, air transport of medical device batteries is common. Whereas industries like eCommerce have moved away from reliance on air transportation, medical device shippers must utilize air transport to deliver their batteries and devices to patients without delay. One reason medical device battery shippers are confident in the safety of their air shipments is the quality of the batteries themselves. The lithium cells and batteries used in these devices are state-of-the-art in terms of performance, quality, and safety. Their cells and batteries are under strict scrutiny not only from the U.S. Department of Transportation, but from the Food and Drug Administration (FDA) as part of the requirements of being a regulated medical device.

Cells and batteries that power implantable devices such as pacemakers and neuromodulators are often lithium metal chemistry and shipped inside custom molded plastic trays. These trays, like the button cell examples previously shown, have divots that are custom cut to fit a specific cell or battery (see Figure 10 below for packaging example). In the medical field, companies often must sterilize devices and batteries prior to shipment. In these circumstances, the cells are either sterilized within the trays or are sterilized and individually placed into sealed plastic bags. The plastic tray or sealed plastic bag (sometimes referred to as a sleeve) serves to meet the inner packaging requirements. As needed, filler materials such as bubble wrap, paper, or air bags are placed into the package as a stabilizer.

The high value of medical device batteries justifies an investment in higher integrity packaging. Medical device battery shippers often use double-walled, UN 4G fiberboard boxes as an outer package, even when not necessarily required per Section IB provisions for standalone lithium ion and metal cells and batteries.

[20] *Definition of medical device per 49 CFR §173.185: Medical device means an instrument, apparatus, implement, machine, contrivance, implant, or in vitro reagent, including any component, part, or accessory thereof, which is intended for use in the diagnosis of disease or other conditions, or in the cure, mitigation, treatment, or prevention of disease, of a person.*

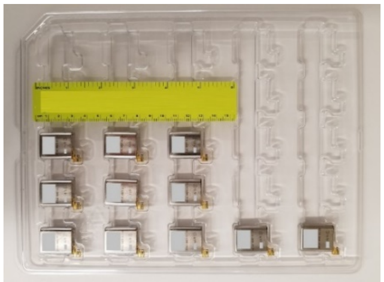	• After manufacturing, the cells are placed in a shipping tray • The shipping tray is formed of a rigid plastic with pockets of the size and shape of the cells • Cells are well separated and secured in the shipping tray to prevent shifting during transport • Connectors are well protected to prevent short • A clear rigid plastic cover is clipped over the shipping tray to maintain the cells in their secured pockets
	• The covers and shipping trays are securely kept close by 4 shrink-wrap bands *(not easily visible inside the green frames)* • The shipping trays are then placed inside a sealed plastic bag
	• The shipping trays are placed in a double-wall cardboard box • The shipping trays are protected by layers of cushioning packing materials • The cardboard box is closed
	• The closed cardboard box is placed inside a UN 4G Fibreboard box

Figure 10
Example medical device cell packaging

Air Carrier Safety Beyond the Package Level

It is the responsibility of the shipper to properly package, mark, label, and document each lithium battery shipment. Preparing lithium battery shipments in accordance with the regulations is the first step to ensure transportation safety, but it is not the only step. Once prepared, the shipper offers packages to their carriers for delivery to final destinations. Air carriers rely on their shippers to properly classify, package, and communicate the hazards associated with the package contents. Though the onus is on shippers to comply with applicable regulations, carriers also have responsibilities when it comes to accepting packages for transport. Per 49 CFR §171.2(f), "Each carrier who transports a hazardous material in commerce may rely on information provided by the offeror of the hazardous material or a prior carrier, unless the carrier knows or, a reasonable person, acting in the circumstances and exercising reasonable care, would have knowledge that the information provided by the offeror or prior carrier is incorrect." As a result, air carriers perform detailed acceptance checks on fully regulated (e.g., packages with hazard class labels and shipping papers) to ensure each package is prepared in accordance with the applicable regulations, including package configuration, proper markings and labels and is accompanied by a compliant shipping paper. Because many major air carriers do not accept standalone lithium batteries packed in accordance with the Section II requirements, most standalone lithium battery packages undergo an acceptance check because they are required to have a hazard class label and a shipper's declaration for dangerous goods. These checks, typically carried out by knowledgeable staff following a set acceptance checklist, weed out non-compliant packages. These acceptance checks serve as another safety measure in the transport chain.

Once packages are accepted for loading on an aircraft, there are various measures air carriers employ to mitigate risks associated with lithium batteries. To gain further insight on air carrier handling procedures related to lithium battery packages, HSC surveyed air carriers that are members of the COSTHA Air Carrier Roundtable (ACRT). Given that standalone lithium cells and batteries are not permitted on passenger-carrying aircraft, we have focused on the safety procedures employed by air carriers that operate cargo-only aircraft. A summary of their reported risk mitigation measures is reported below.

Loading and Segregation Procedures

In accordance with 49 CFR §175.78(b)(2), Section IA/IB lithium battery packages cannot be stowed on an aircraft next to, in contact with, or in a position that would allow interaction with packages that bear Class 1 (other than Div. 1.4S), Division 2.1, Class 3, Division 4.1, or Division 5.1 hazard labels. Due to the possibility of thermal runaway acting as an ignition source, packages containing flammable, oxidizing, or explosive contents may not be in proximity to lithium batteries. When loading the aircraft, air carriers reported that fully regulated lithium battery packages (e.g., Section IA/IB) are identified and segregated from all other hazardous materials subject to the accessibility requirements of 49 CFR 175.75(d)(1). As Class 9 materials, lithium batteries are exempt from these accessibility requirements. When hazardous materials requiring accessibility are present, lithium battery packages are separated from those materials by at least one position to ensure no contact or proximity to other hazardous materials. When no freight requiring accessibility is aboard, lithium batteries may be loaded anywhere on the aircraft.

Safety Procedures Related to Overpacks

Overpacks, which are enclosures used by a single consignor to provide protection or convenience in handling of a package, or to consolidate two or more packages, are commonly shipped via all transport modes (see Figure 11 for example). To mitigate risks of hazardous materials in proximity to lithium batteries, packages containing standalone lithium batteries must not be placed into an overpack with packages containing hazardous materials and articles of Class 1 (explosives) other than Division 1.4S, Division 2.1 (flammable gases), Class 3 (flammable liquids), Division 4.1 (flammable solids) or Division 5.1 (oxidizers). Air carriers rely on shippers to follow these restrictions when accepting overpacks. Based on the carrier survey, overpacks containing lithium batteries are fairly common, but the airlines themselves do not track frequency of overpacks offered for transport. One carrier reported that overpacks containing lithium batteries are only accepted in a select few of their freight services. IATA confirmed that there is no reliable information on how many lithium battery shipments are moving in overpack configurations.

Figure 11

Unit Load Devices (ULDs)

For air transport, shippers often offer packages individually rather than in complete pallets. These individual packages are collected from businesses and residences and driven via highway to air terminals to prep for transport. Individual packages are then often placed into Unit Load Devices (ULD; see Figure 12), which allow for consolidation of packages into one unit that makes loading/unloading the aircraft more efficient. Additionally, many businesses and third-party logistics facilities load lithium battery packages directly into ULDs on-site, which are monitored by airline employees and transported to airline facilities. These ULDs allow for increased efficiency as well as, in many cases, additional risk mitigation for lithium battery packages. Based on our carrier survey, operators prioritize ULDs for lithium battery packages. This practice means lithium battery packages are identified, segregated, and loaded into available ULDs before other materials. Whether all battery packages are enclosed in ULDS depends on the number of ULDs available and the amount of battery packages to be loaded onto the plane. While ULDs vary by design and safety feature, many are considered fire-resistant because they are constructed of aluminum, which according to Federal Aviation Regulations is considered fire-resistant (14 CFR §1.1). Further, some ULDs have additional thermal performance material that lines the doors of the ULD.

ULDs have long been recognized as a key piece of a multi-layered safety approach. The ULDs in circulation today are often constructed of robust materials that provide an added layer of protection between a package and the fuselage of an airplane. As lithium battery transportation safety continues to be an area of focus among pilots, regulators, and airframe manufacturers, we can expect more and more technological advances to ULDs such as internal fire suppression capabilities, thermal management materials, and early detection systems. We recommend PHMSA advocate the construction and use of these types of ULDs in the future.

Figure 12

Fire Covers

In addition to ULDs, respondents to our air carrier survey indicated that use of fire covers are becoming increasingly common (see Figure 13 for example). For palletized loads not contained in ULDs, a fire containment cover (FCC) offers an added layer of protection. The carriers responding to our survey indicated that, like ULDs, lithium battery packages are given priority for use of FCCs. Additionally, one carrier indicated that it is common practice to use FCCs on lithium battery packages when the duration of the flight meets certain criteria. These fire covers come in various shapes and sizes, but the functionality of them is the same: they are meant to lay atop packages or pallets, and provide a thermal shield should a fire ignite as a result of a lithium battery thermal runaway or another initiation source. Like ULDs, these fire covers also provide some protection against a fire that may have originated elsewhere on the aircraft but has spread to the position in which batteries are stowed (i.e., external fire).

Figure 13

Tests have been conducted on FCCs and many have demonstrated an ability to contain a fire involving lithium batteries. A 2015 test involving 1,500 lithium ion cells driven to thermal runaway revealed the cover contained the fire for 6 hours, even though the fiberboard packaging within the overpack burned and all cells vented.[21]

Air Carrier Recommendations

Air operators and pilots are very aware of the dangers posed by lithium batteries. Unfortunately, the reality is that not all shippers offer packages in compliance with regulatory standards, which leads to elevated risks for air carriers. This has caused air operators to implement additional safety measures such as fire containment covers, fire-resistant ULDs, increased staff training, and loading restrictions. Respondents to our survey indicated they would welcome increased enforcement measures against non-compliant shippers, better outreach and guidance to make the regulations more understandable to everyday shippers, adoption of the SAE G-27 packaging standard, and public awareness campaigns to educate citizens on the dangers of lithium batteries and that they are subject to transportation regulations.

---

[21] Jamaldeen, S. 2015. *Fire Containment Cover Lithium Ion Battery Fire Tests.* International Aircraft Systems Fire Protection Working Group Meeting. Oct 21 – 22, 2015. https://www.fire.tc.faa.gov/pdf/systems/Oct15Meeting/Jamaldeen-1015-FCCLithiumTest.pdf

LITHIUM BATTERY PACKAGING OPTIONS

The regulations require that lithium cells and batteries be completely enclosed within an inner packaging. The regulations are not specific as to what type of inner packaging must be used to meet this requirement. For lithium batteries, many shippers opt to use plastic inner packagings, typically plastic bags or blister packs. Bags are an attractive option because they are low cost and can be sourced for any size/shape cell or battery. In many off-the-shelf lithium battery shipper kits sold by suppliers, anti-static or static shielding plastic bags are provided. Standard plastic bags are useful in creating a strong, flexible barrier between the cells/batteries and other contents in the package. This barrier serves to prevent the likelihood of a short circuit due to contact with conductive materials in the package, including other batteries. Anti-static bags are plastic bags that will not build static charge as they shift inside a package, while static-shielding bags have multiple levels that both prevent static electricity build up and protect against electrostatic discharge (ESD). In addition to bags, shippers use anti-static plastic cushioning material such as anti-static bubble wrap. Anti-static and static shielding bags and cushioning material may represent a best practice and, according to our surveys, they are frequently used, but they are not required for use. Though plastics are common, other inner and intermediate packagings and cushioning materials such as cardboard egg crates, foam inserts, retail cardboard packagings, and clamshells are used to protect the battery from damage caused by impact or short circuit.

There are many companies that offer off-the-shelf packaging for the transport of lithium batteries ranging from simple fiberboard boxes to metal reusable packages. The packaging varies in cost, from as little as $2.00 per box to $1,000 or more for custom designed reusable packaging. One representative from a battery trade association estimates that upwards of 95% of lithium cells and batteries are shipped in fiberboard boxes. For small cells and batteries that are excepted from UN Performance Packaging requirements, a rigid, strong fiberboard box is common. For higher energy cells and batteries, UN 4G fiberboard boxes are the norm.

There are numerous packaging suppliers that offer non-specification fiberboard boxes. These types of packages are inexpensive, durable, easy to assemble, and have become the most common outer packaging for transporting small lithium cells and batteries. The regulations require that these packages be “strong and rigid” as well as capable of passing a 1.2-meter drop test without release of contents or damage to batteries. Suppliers of non-specification fiberboard boxes do not typically advertise their boxes as capable of withstanding a drop test. Instead, suppliers use industry fiberboard strength metrics such as Edge Crush Test (ECT) and Mullen test (burst strength) to describe the strength of their packages. ECT measures the box board’s top-to-bottom compression strength (see Figure X). This test involves compressing a small segment of fiberboard on edge between two rigid plates. During this test, it is determined how many pounds per lineal inch the fiberboard can bear before collapsing. The pressure (lbs./in.) the fiberboard can withstand is how ECT is derived. For example, a fiberboard wall bearing 32 lbs./in. would have an ECT value of 32. It is recommended that shippers rely on ECT rating if their packages are moving through modern distribution environments where palletized stacking is common.

The other test widely used in the fiberboard industry is the Mullen Burst test. Unlike the ECT, which tests top-to-bottom compression force, the Mullen test applies force to the sidewall of the fiberboard to gauge how much pressure it takes to burst or puncture the fiberboard (see Figure 14). The bursting strength is reported in pounds. For example, a fiberboard sidewall that bursts when subjected to 200 lbs. per square inch would have a Mullen burst rating of 200 – often referenced as a 200# box. It is recommended that shippers rely on burst strength if their packages move through rough handling environments where they may be subject to internal or external forces on the box.[22] Achieving higher ECT ratings and burst strength can be achieved using double-walled fiberboard, alternations of flutings, and the wall thickness of the fiberboard.

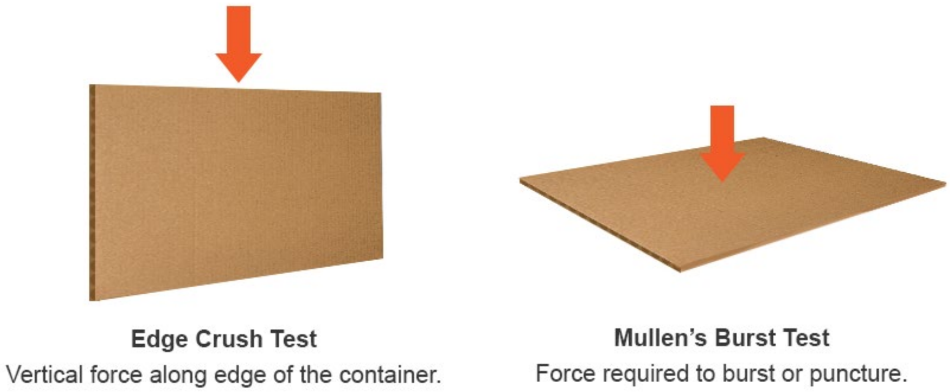

Figure 14 (credit: Rocket Industrial)

The two tests – ECT and Mullen burst strength – are performance tests that measure how different forces impact box integrity. Because they are different, there is no *exact* match between the two (i.e., 32 ECT is the exact same as 200# Mullen rating), but the packaging industry uses comparisons like the one shown below in Figure 15.

Corrugated Board Strength Equivalencies:
Single Wall Corrugated

Bursting Test	Minimum Edge Crush Test	Maximum Suggested Loading Limit Per Carton
125#	23 ECT	20 lbs.
150#	26 ECT	35 lbs.
175#	29 ECT	50 lbs.
200#	32 ECT	65 lbs.
275#	44 ECT	95 lbs.
350#	55 ECT	120 lbs.

Corrugated Board Strength Equivalencies:
Double Wall Corrugated

Bursting Test	Minimum Edge Crush Test	Maximum Suggested Loading Limit Per Carton
200#	42 ECT	80 lbs.
275#	48 ECT	100 lbs.
350#	51 ECT	120 lbs.
400#	61 ECT	140 lbs.
500#	71 ECT	160 lbs.
600#	82 ECT	180 lbs.

Figure 15[23]

---

[22] Allaway, D. 2005. *Bursting Strength vs. Edge Crush Test.* Packaging Waste Reduction Best Practices. State of Oregon, Department of Environmental Quality, Land Quality Division Solid Waste Policy and Program Development Section.

[23] Allaway, D. 2005. *Bursting Strength vs. Edge Crush Test.* Packaging Waste Reduction Best Practices. State of Oregon, Department of Environmental Quality, Land Quality Division Solid Waste Policy and Program Development Section.

Since packaging suppliers typically advertise either/both bursting test and ECT, shippers can use this type of guidance to determine which box specifications are best for their shipments. Unlike UN Performance fiberboard boxes where the maximum gross mass is marked on the package, shippers must use burst strength metrics or ECT to determine the maximum suggested mass per box. For air shipments of “small” lithium batteries (e.g., lithium ion cell ≤ 20 Wh) under the Section IB provisions, UN-rated packaging is not required. Since the authorized net weight of batteries per package under the Section IB requirements is fairly low (10 kg for UN3480, 2.5 kg for UN3090), shippers are unlikely to need a package with a maximum weight limit of more than 65 pounds, which correlates to a 200# or 32 ECT fiberboard. A review of the top 50 best-selling non-specification fiberboard boxes from a leading supplier reveals all are rated to a 200# burst strength, regardless of package dimensions.

Respondents to our survey indicated that they use factors like ECT rating, burst test, and wall thickness to ensure the package meets requirements of strength and rigidity. Further, 88% of respondents indicated that their company performs and documents the 1.2-meter drop test on their packaging. Because the regulations mandate packages be “capable” of passing this test, some shippers interpret that to mean the test does not actually have to be conducted and other factors like ECT, burst strength, and previous shipping history can indicate a package is capable of surviving the drop without damage.

For higher energy cells and batteries (i.e., lithium ion battery over 100 Wh), UN Performance Packaging is required, though batteries weighing more than 12 kg with impact-resistant outer cases do not require UN Performance Packaging for air transport provided they have been approved by PHMSA. UN Performance Packages are required to be designed, constructed, and tested to specific standards intended to ensure the packaging is robust enough to contain hazardous materials in transportation. Non-bulk UN Performance Packages are subject to the construction and test requirements of 49 CFR Part 178, Subparts L and M. UN-rated fiberboard boxes (UN 4G) – the most frequently used UN packaging for air transport of lithium batteries – are subject to the packaging standards of 49 CFR §178.516. The regulations mandate the outer surface of the fiberboard be water-resistant as determined by the Cobb method for water absorption.[24] Manufacturers must ensure the box joints are taped, lapped and glued, or stitched with metal staples. The maximum net mass of a UN 4G fiberboard box is 400 kg (882 pounds).

After manufacturing, UN 4G boxes must pass a series of three tests to be certified as UN-rated. Subpart M of Part 178 spells out required tests for non-bulk UN-rated packagings. These tests are:

- Drop Test (§178.603)
- Leakproofness Test (§178.604)
- Hydrostatic Pressure Test (§178.605)
- Stacking Test (§178.606)
- Cooperage Test (§178.607)
- Vibration Standard (§178.608)
- Test Requirements for Infectious Substances (§178.609)

Of the seven (7) tests listed above, UN 4G boxes intended to contain lithium batteries are subject to only three (3): Drop Test, Stacking Test, and Vibration Standard.

The drop test is intended to demonstrate that the outer packaging is capable of withstanding a drop from a certain distance without releasing its contents or sustaining damage likely to affect safety in transportation. To certify a UN 4G box for Packing Group I materials, the sample packages must be dropped in required orientations from a height of 1.8 meters (5.9 feet). For Packing Group II certification, the drop height is 1.2 meters (3.9 feet), while Packing Group III boxes must withstand a drop of 0.8 meters (2.6 feet).

[24] Cobb Test described in ISO 535 (IBR, see 49 CFR §171.7)

The stacking test is intended to demonstrate that the package is capable of withstanding a top load force. To successfully pass this test, the package must withstand a stacking force equivalent to identical-weight packages stacked up to a height of 10 feet (3.0 meters) for a 24-hour duration. Take, for example, a package with a rated gross mass of 25 kilograms at dimensions of 12 in. x 12 in. x 12 in. To properly conduct the test, one must stack nine (9) identical packages – each filled to rated capacity – atop the bottom package for at least 24 hours. After the 24-hour duration has elapsed, the stack must still be intact and the package on the bottom cannot show deterioration or damage likely to affect safety in transportation.

The final test, the vibration standard, consists of subjecting packages to a vibrating platform for one hour where the packages are bounced at a certain frequency. This test is meant to simulate vibrations common to all modes of transport. To pass the test, the package must show no signs of leakage or damage that could adversely affect transportation safety. The vibration standard is geared toward assessing how vibration affects closures and the structural integrity of inner packages containing liquids. For articles such as lithium batteries, the usefulness of the vibration test is in question.

For a novice shipper, identifying compliant UN-rated boxes is often difficult. There are many companies that offer off-the-shelf UN 4G boxes to be used for transporting lithium cells and batteries. A UN Performance Package must be tested in the configuration of the finished package. This means that the fiberboard box and all inner packagings, including cushioning material and the contents to be transported (or simulated articles of the same weight and shape), must undergo testing in its final assembled configuration that will be used for transport. There are regulatory provisions that allow some flexibility in terms of number and configuration of inner packagings. These provisions – referred to as “variations” – allow shippers to fill and ship UN Performance Packages with inner packagings that do not exactly match those for which the package was originally tested. Use of these variations is important for lithium battery shippers because lithium batteries come in a wide range of sizes, shapes, and weights, which makes it unreasonable for packaging manufacturers to test packages for every type of lithium battery. Instead, shippers and manufacturers utilize the variations provided in 49 CFR §178.601(g).

Variation 1 – 49 CFR §178.601(g)(1) – authorizes changes in inner packaging provided the inner packaging is (1) of equivalent or smaller size, (2) of similar design, (3) constructed with materials that offer equal or greater resistance to impact and stacking forces as the tested inner packaging, (4) have same or smaller openings and equivalent closure design, (5) secured in the package with sufficient cushioning materials, and (6) in the same orientation. For packaging manufacturers, Variation 1 provides flexibility to their customers. After review of manufacturer UN Performance Packaging test reports for boxes advertised as lithium battery shipping packages, many are tested with a single, large lithium battery inside a plastic anti-static bag or, in other cases, simulated articles and lead shot simulate weight and shape of a battery. When the box passes the design qualification test in this configuration, shippers use Variation 1 flexibility to pack the box with multiple batteries – each in an anti-static plastic bag – up to the rated gross weight marked on the package. Per the conditions of Variation 1, this practice is not prohibited. However, there is a requirement that the methodology used to justify Variation 1 be documented and maintained. Packaging manufacturers typically sell packaging to customers with the explicit warning that the package is certified based on tested materials and it is the shipper’s responsibility to determine compliance when filling the package with other materials. It is doubtful all shippers are creating justification documentation.

To be able to sell boxes for a wider range of contents, some packaging suppliers utilize the Variation 2 test procedures – as detailed in 49 CFR §178.601(g)(2) – because it allows more flexibility to the shipper in terms of contents and configurations of cells and batteries. Variation 2 authorizes articles or inner packagings of any type in the outer package provided it meets the following conditions:

- The outer package must be tested at PG I drop test height (1.8 m) with fragile inner packagings containing liquids (e.g., glass bottles);
- The combined gross mass of the inner packagings may not exceed one-half the gross mass of inner packagings used for the drop test;
- The thickness of cushioning material between inner packagings and between inner packagings and the outside of the packaging may not be reduced below the corresponding thickness in the originally tested packaging; and when a single inner packaging was used in the original test, the thickness of cushioning between inner packagings may not be less than the thickness of cushioning between the outside of the packaging and the inner packaging in the original test. When either fewer or smaller inner packagings are used (as compared to the inner packagings used in the drop test), sufficient additional cushioning material must be used to take up void spaces.
- The outer packaging must have successfully passed the stacking test set forth in §178.606 of this subpart when empty. The total mass of identical packages must be based on the combined mass of inner packagings used for the drop test;
- Inner packagings containing liquids must be completely surrounded with a sufficient quantity of absorbent material to absorb the entire liquid contents of the inner packagings;
- When the outer packaging is intended to contain inner packagings for liquids and is not leakproof, or is intended to contain inner packagings for solids and is not sift proof, a means of containing any liquid or solid contents in the event of leakage must be provided in the form of a leakproof liner, plastic bag, or other equally efficient means of containment. For packagings containing liquids, the absorbent material required in paragraph (g)(2)(v) of this section must be placed inside the means of containing liquid contents; and
- Packagings must be marked in accordance with §178.503 of this part as having been tested to Packing Group I performance for combination packagings. The marked maximum gross mass may not exceed the sum of the mass of the outer packaging plus one half the mass of the filled inner packagings of the tested combination packaging. In addition, the marking required by §178.503(a)(2) of this part must include the letter "V".

Variation 2 boxes would have the most value in circumstances where a shipper has wide varieties of batteries that they ship. However, it's unlikely they are widely used for lithium batteries because the provisions regarding the cushioning material thickness cannot be met in all cases due to the irregular shape of some high energy lithium batteries. Test reports for many UN 4GV boxes reveal that the original design qualification testing was conducted using glass bottles containing liquids, which differ from lithium batteries in terms of shape and volume. While these types of boxes offer flexibility for various inner packagings, they are of more value for shipping liquid hazardous materials in different inner packagings than for lithium batteries. In cases where they can be used, manufacturers can sell the packages to shippers that have a need for such flexibility. For the novice shipper, Variation 2 packaging cuts through much of the confusion regarding UN Performance Packaging test and allows shippers to mix and match cells/batteries in different configurations provided they are not exceeding the marked maximum gross mass of the package and are closing the package in accordance with the instructions.

With that said, UN Performance Packaging regulations, including those tested to Variation 2 standards, are complicated. Responsibility for compliance is placed upon the shipper, not the packaging manufacturer. As a result of complexity and liability concerns, packaging manufacturers are often reluctant to provide detailed guidance to shippers regarding the exact types and configurations of cells or batteries that are authorized in each package. This leads to non-compliant use of UN-rated packaging, especially when the buyer of the packaging works in procurement and has not received any dangerous goods training.

As a result of the complexities of manufacture and testing, packaging suppliers commonly charge more for UN-rated fiberboard boxes than a standard, non-specification boxes of the same size. HSC reviewed publicly available pricing from packaging suppliers to compare how price differs between UN-rated boxes and those that are not UN-rated. The table below highlights UN-rated boxes sold as “lithium battery shippers” by popular suppliers in comparison to a similarly size non-specification package. The boxes advertised as lithium battery shippers were chosen because those packages were tested with lithium batteries (or articles representative of batteries) inside. Per the Hazardous Materials Regulations, packages must be tested with the contents they intend to hold; a shipper cannot select any UN 4G-rated box and place their batteries inside as the box may not have been tested with batteries or articles simulating batteries inside. It should also be noted that this is not exactly a one-to-one comparison as the UN-rated lithium battery shipping boxes sometimes are sold with vermiculite or anti-static inner bags and advertised as kits. Still, this comparison highlights cost discrepancies between UN-rated fiberboard boxes and non-rated boxes. The pricing for non-specification boxes come from a single, popular supplier (ULINE). All non-specification boxes have a Mullen test (burst strength) rating of 200 pounds.

Box Dimensions (± 1 in.)	9” x 9” x 9”	15” x 15” x 15”	16” x 11” x 9”
Non-Specification Price Per Package for Order of 100 Boxes	$0.63 (X)	$1.53 (X)	$1.33 (X)
Supplier #1 UN-Rated Boxes Price Per Package for Order of 100 Boxes	$6.86 (10.9X)	$9.71 (6.3X)	$8.06 (6.1X)

Box Dimensions (± 1 in.)	9” x 9” x 9”	15” x 15” x 15”	10” x 5” x 5”
Non-Specification Price Per Package for Order of 100 Boxes	$0.63 (X)	$1.53 (X)	$0.65 (X)
Supplier #2 UN-Rated Boxes Price Per Package for Order of 100 Boxes	$4.88 (7.7X)	$10.97 (7.2X)	$2.42 (3.7X)

Box Dimensions (± 1 in.)	6” x 6” x 6”	12” x 12” x 12”	14” x 14” x 14”
Non-Specification Price Per Package for Order of 100 Boxes	$0.35 (X)	$0.85 (X)	$1.33 (X)
Supplier #3 UN-Rated Boxes Price Per Package for Order of 100 Boxes	$5.99 (17.1X)	$12.00 (14.1X)	$14.99 (11.3X)

Box Dimensions (± 1 in.)	9” x 5” x 5”	12” x 12” x 12”	15” x 15” x 15”
Non-Specification Price Per Package for Order of 100 Boxes	$0.39 (X)	$0.85 (X)	$1.53 (X)
Supplier #4 UN-Rated Boxes Price Per Package for Order of 100 Boxes	$1.90 (4.9X)	$6.00 (7.1X)	$8.00 (5.2X)

The data clearly indicate that UN-rated packages are much more costly than non-specification boxes of a similar size. Shippers can bring down UN Packaging costs via high volume purchasing, but a gap between UN-rated packaging and non-specification packaging is likely to persist. Take, for example, a high-volume shipper that uses UN 4G boxes with dimensions of 15” x 15” x 15” for their high-energy batteries, they are paying from 5.2 to 7.2 times the cost of a non-specification box. If we meet in the middle with a 6.2 multiple, the company is paying $9.49 per package, whereas each non-specification package costs $1.53. Assuming the company ships 100,000 battery packages per year, they are paying $796,000 more for their UN-rated packages as compared to a non-specification package of the same dimensions ($949,000 - $153,000 = $796,000). This leads us to question how much added safety is being gained from that additional $796,000 expenditure?

For lithium battery shipments, the answer may be minimal. Along with the water resistance, the three required UN performance tests (drop, stack, and vibration) are meant to give UN 4G boxes a higher degree of safety than alternative, non-specification boxes. However, under review there is not much separating these types of boxes. To start, the value of a vibration test on articles such as lithium batteries is minimal. Further, lithium batteries are already subject to vibration testing via Test T.3 of the UN Manual of Tests and Criteria, Part III, Subsection 38.3. There are also minimal differences between UN-rated packages and non-specification boxes when it comes to drop testing. High-energy (e.g., over 100 Wh) lithium batteries must be shipped in PG II-rated UN packages. To achieve PG II level, the package must withstand multiple drops in different configurations at a drop height of 1.2 meters. For small (e.g., under 100 Wh) lithium batteries as well as those packed with equipment that are authorized in non-specification strong outer packagings, the package must already be capable of withstanding a 1.2-meter drop. While the UN packaging tests are more prescriptive in terms of number of samples and drop orientation, the basic principle is that both packages must withstand a 1.2-meter drop. The final test, stack test, also has similar performance metrics for non-specification packages. Most non-specification box suppliers advertise either Mullen burst test strength or edge crust test (ECT) rating. The ECT test is a direct measure of the ability of the box to withstand a top load stacking force. The Mullen test, on the other hand, applies to the burst pressure of the fiberboard. However, industry standard is that a box rated to 200 lbs. on a Mullen test is equivalent to a 32 ECT box. Going back to our previous example of the 12" x 12" x 12" box stack test, the lowest box in the stack would have to withstand a top force of 180 kg (9 boxes at 20 kg apiece). In the packaging industry, there is a similar measure, known as the Box Compression Test (BCT) strength, which can be estimated using the McKee formula below:

$$BCT = k1 \times ECT \times \sqrt{h \times Z}$$

K_1 = constant value of 5.87
ECT = Edge Crush Rating
h = fiberboard thickness
Z = box perimeter 2(L + W)

For this example, the non-specification box has 12" x 12" x 12" dimensions, fiberboard thickness of 0.25" and a 32 ECT rating. This gives a BCT value of 650 pounds (295 kg), which is greater than the stacking force required for the UN 4G stack test. With that said, the BCT estimates the maximum weight a box can handle for a given moment, whereas the UN 4G stack test requires a 24-hour duration. Even so, the momentary weight the box can support (295 kg) far exceeds the amount required for the physical stack test of §178.606 (180 kg). In addition, for periodic retesting §178.606 authorizes the use of a dynamic compression testing machine. When using the machine, the regulations require a 1.5 multiplier, meaning in our example the weight applied by the compression machine would be 270 kg (180 kg x 1.5). The BCT estimate of 295 kg for our non-specification box also exceeds the weight required when using a dynamic compression machine. BCT is intended as an estimate. Studies suggest that the ability of McKee formula to predict actual tested stacking force is far from perfect. Most boxes become weaker as the height is increased due to wall buckling and, as a result, the calculated BCT of a taller box will overestimate the box's actual ability to withstand stacking force. On the other hand, the BCT derived from the McKee formula will underestimate the box's ability to withstand stacking force for boxes that are short.[25]

The UN Performance Packaging tests are qualification tests and do not serve as confirmation that a package will withstand the rigors of a typical distribution environment. These qualification tests are intended to demonstrate that the package is capable of withstanding certain forces (in the UN 4G case, it's stack force, drop force, and vibration) and that repeatable results are obtained when the same package is tested by different labs. In modern distribution environments, packages are subject to a wide variety of rough handling, stacking, and drop heights throughout the supply chain. Unfortunately, the UN Performance tests do not assess

[25] Aloumi, B., et. al. 2015. 'Experimental Verification of McKee Formula', *International Journal of Advanced Packaging Technology,* volume 3, issue 1, pp. 129 – 137.

how package integrity is degraded due to the cumulative effects of these stressors. In the UN testing scheme for fiberboard boxes there are five (5) required drops from 1.2 m (PG II level) on five (5) separate packages. This tests for an ability to withstand a one-time impact but does not provide verification that the same package will withstand, for example, 5 drops from a lesser height as well as stacking force for 48 hours. This is not to say that UN Performance Packaging tests lack value, but it is helpful to highlight limitations of any testing scheme. Standards groups, particularly ASTM International (ASTM) and International Safe Transit Association (ISTA) have developed tests that subject packages to test conditions more representative of modern distribution environments. These tests include:

- ASTM D4169 – 16: Standard Practice for Performance Testing of Shipping Containers and Systems
- ISTA Procedure 1A: Packaged-Products weighing 150 lbs. or less
- ISTA Procedure 3A: Packaged-Products for Parcel Delivery System Shipments 150 lbs. or less
- ISTA Procedure 6A: Member-Specific Test Standards

Tests such as these have been widely adopted throughout the industry, especially in eCommerce and parcel shipping environments, and represent an industry best practice for supply chain safety.

After our review and subsequent discussions with independent packaging test lab representatives, it is our belief that the required UN Performance tests for combination packagings are not well suited to packages containing articles such as lithium batteries. For combination packagings meant to contain liquids in inner packagings, the UN Performance tests are vital to ensure exposure to vibration and drop force do not damage inner packagings and their closures to the extent that leakage occurs. For lithium batteries, however, leakage is not a primary concern; the more pressing issue is whether the battery will sustain damage likely to lead to a thermal runaway event. And, unlike liquid inner packagings that are not tested on their own, the UN Performance vibration and drop tests are redundant to those the lithium cells or batteries must already complete in the UN Manual of Tests and Criteria 38.3 test scheme (Vibration: T3, T4; Impact: T6). Given the costs associated with UN Performance packages already detailed, it is not apparent that shippers are getting additional safety in exchange for higher costs.

Drums are not typically used to ship new batteries by air, but in some cases are used for shipping prototype batteries by air. Prototype batteries are forbidden for transport aboard passenger aircraft. Transport on cargo aircraft is permitted under the approval of the competent authority of the State of Origin, which means the country where the shipment will be loaded onto the aircraft. If shipping prototype batteries from multiple locations, you need an approval from each country of origin. Regardless of the State of Origin, if you ship to, from, or within the U.S an approval according to US variation US-03 is required from the US DOT, PHMSA in addition to any other approvals that have been issued by other competent authorities.

In the United States, the most common approval for air shipments of prototype lithium batteries is provided in DOT Special Permit 20323, to which more than 30 companies have party status. The outer packaging required per this permit is Packing Group I-level metal packagings. In most cases, shippers use small UN 1A2 steel pails (drums) as the outer package. To meet its equivalent level of safety standard, PHMSA mandates a more robust package (i.e., metal outer package instead of fiberboard/wood/plastic) that is more likely to contain the hazards associated with a thermal runaway event (though it is not explicitly required to do so) from a lithium cell or battery that has not completed the UN 38.3 test procedure. This type of packaging is more protective against extreme heat and fire, though concerns remain around shipping lithium batteries inside of sealed drums or boxes. During thermal runaway, many cells produce liters of gas – which contains flammable constituents. Without the ability to vent the gas, sealed packages are at risk of overpressure and/or rapid gas ignition which may be as catastrophic to an airplane as a fire involving a lithium battery in a fiberboard box. There does not appear to be publicly available test data regarding the performance of sealed packaging during thermal runaway events. However, based on discussions with one test lab, their tests have shown that off-gassing caused the pressure to build up inside the pail, causing the pail to rupture. And in the case where 18650 cells at near 100% SOC are used in the battery pack, the contained gasses ignite before the pail vents, causing a catastrophic explosion. It is due to these concerns that Packing Instruction P908 in the UN Model Regulations states, “Sealed packagings shall be fitted with a venting device when appropriate.” The HMR has no such provision for lithium battery packaging explicitly but does have general packaging requirements surrounding venting and build-up of gas in 49 CFR §173.24(g). In this paragraph it is noted that venting of a packaging to reduce internal pressure is authorized only when transportation by aircraft is not involved and the evolved gases are not poisonous nor likely to create a flammable or toxic atmosphere under normal conditions of transport. As battery failure analysis has revealed, off-gassing of lithium batteries is likely to include constituents that are both flammable and toxic. Venting these gases may constitute a violation of 49 CFR §173.24(g). It is our recommendation that PHMSA adopt the language found in the UN MR regarding sealed packagings. Instead of amending 49 CFR §173.24(g), PHMSA may consider adding the following text in 49 CFR §173.185(b)(1):

> (b) *Packaging.* (1) Each package offered for transportation containing lithium cells or batteries, including lithium cells or batteries packed with, or contained in, equipment, must meet all applicable requirements of subpart B of this part. *Irrespective of §173.24(g), sealed packagings shall be fitted with a venting device when appropriate.*

This language gives shippers the ability to assess their packaging and, if necessary, offer packages capable of venting off-gas that could lead to an overpressure and explosion of the packaging itself. There are understandable concerns regarding off-gas on a cargo aircraft, however, the volume of air within the cargo hold is far greater than that in the sealed packaging, making a buildup of a flammable atmosphere in the cargo hold significantly less likely.

There are alternatives to sealed packagings for prototype air shipments. For example, DOT SP 20798, which authorizes the manufacture, mark, and sale of packages for air shipments of prototype lithium cells and batteries that are capable of containing a thermal runaway event, in the unlikely case that one occurred.

In May 2020, the NTSB released a report that included a recommendation to prohibit air transportation of prototype lithium cells and batteries under any circumstances.[26] Such a ban would damage product development cycles, which often require the ability to move prototype or low production run cells and batteries to various locations in a timely manner. Further, it is not clear the risks justify an outright prohibition. The current approach of Competent Authority Approval is sufficient, though it is recommended that PHMSA review existing Special Permits and Approvals regarding prototype air shipments to ensure an equivalent level of safety.

[26] *Safety Recommendation Report Standards for Lithium-ion Battery Shipments by Air. National Transportation Safety Board, NTSB/HZMSR-20/01. May 28, 2020.*

REGULATORY & INDUSTRY SAFETY INITIATIVES

SAE G-27 Lithium Battery Packaging Performance Committee

A new focus on packaging performance has been initiated in recent years based on recommendations made by ICAO on three Multidisciplinary Meetings and by the United Nations Transport of Dangerous Goods Sub-Committee (UN TDGSC). ICAO members affirmed that a fire involving significant quantities of lithium batteries (UN 3090 and UN 3480) could exceed the fire suppression capability of the aircraft and could lead to a catastrophic failure of the air frame. They concluded that there is a need to develop performance-based standards on the principle that hazardous effects from the batteries would be contained within the package. Many regulators and safety experts believe that the current requirements are not enough and more needs to be done to mandate appropriate packaging requirements for the transport of lithium batteries, particularly for the air mode. Concerns related to lithium battery hazards were addressed in the Report of the Third International Multidisciplinary Lithium Battery Transport Coordination Meeting[27]:

a) the inability of packaging currently required by the Technical Instructions to contain a lithium battery fire or to prevent the propagation between adjacent packages of batteries;
b) the potential for an uncontrolled lithium battery fires to negate the capability of current aircraft cargo fire protection systems, leading to a catastrophic failure of the airframe; and
c) test results from the Federal Aviation Administration (FAA) William J. Hughes Technical Centre (FAA Tech Centre) which demonstrated the potential for electrolyte gases exhausted during the propagation of both lithium metal and lithium ion batteries to create an explosive atmosphere regardless of the presence of Halon when contained inside an enclosed space such as a unit load device or cargo compartment[28].

As a result of the concerns expressed by regulators, in 2016 the SAE formed the G-27 Lithium Battery Packaging Performance Committee, which is a technical committee in SAE's General Projects Systems Group tasked with developing a minimum performance package standard for the safe shipment of lithium batteries as cargo on aircraft. The committee works in conjunction with related bodies such as the International Civil Aviation Organization, International Air Transport Association, International Federation of Airline Pilots Association (IFALPA), International Coordination Council for Aerospace Industry Association (ICCAIA), European Association for Advanced Rechargeable Batteries (RECHARGE), Rechargeable Battery Association (PRBA), Battery Association of Japan (BAJ), defense agencies, and regulatory authorities. The committee was established at the request of ICAO to develop a performance standard for lithium battery packaging based on the high-level performance standards developed during the third Multidisciplinary Lithium Battery Transport Coordination Meeting.

The focus of the Committee is on the development of the "Performance Based Package Standard for Lithium Batteries as Cargo on Aircraft" – also referred to as the SAE AS6413 standard. Though the standard is not complete, the core concept is to demonstrate that the packaging used for air transport of standalone lithium cells and batteries be capable of containing the hazards associated with a thermal runaway within the package. To demonstrate this, one must initiate a thermal runaway of one cell or battery inside a package in the same

[27] *Report of the Third International Multidisciplinary Lithium Battery Transport Coordination Meeting, ICAO May 8, 2015*

[28] *Webster, H., Fire Protection for the Shipment of Lithium Batteries in Aircraft Cargo Compartments, FAA Technical Center, DOT/FAA/AR-10/31, November 2010. http://www.fire.tc.faa.gov/pdf/10-31.pdf.*

configuration as it will be transported. The tests are conducted inside of a test chamber, which has very strict specifications. To pass the test, it must be shown that:

- No hazardous flame exited the package;
- No hazardous fragment exited the package;
- The average external surface temperature of the package shall not be greater than 100 °C from the pre-test temperature of the package;
- The average temperature for each sensor on any external surface shall not be greater than 100 °C from the temperature at the time the initiation cell entered thermal runaway or from the time of removal of energy to the initiation source in the event the cell did not enter thermal runaway, during the 5 hour remainder of the test [based on a maximum constant sampling period of 10 seconds];
- From the time the initiation cell enters thermal runaway or from the time of removal of energy to the initiation source in the event the cell does not enter thermal runaway, the temperature of each sensor on any external surface shall not increase by more than 150 °C for more than 3 minutes in total during the 5 hour remainder of the test;
- The walls of the package shall have no perforations resulting from this test. Opening of designed pressure relief features and penetrations for test setup is acceptable;
- The package must contain its contents. Release of fastening mechanisms (tape, staples etc.) is acceptable, provided the contents would be contained in any package orientation; and
- The gas collected in the chamber shall not ignite during the test.

ICAO established a prohibition on the transport of lithium batteries as cargo on passenger aircraft in 2016 as a temporary measure until controls were put into place which establish an acceptable level of safety. A performance-based packaging standard was identified as one of the controls. It is anticipated that upon completion of the standard, ICAO will reference the standard in their Technical Instructions, though it is not entirely clear how it will be implemented. The ICAO Dangerous Goods Panel Secretariat has stated that three separate panels (i.e., Airworthiness Panel, Dangerous Goods Panel, and the Flight Operations Panel) will be consulted to determine the how the standard will apply to lithium battery shipments aboard passenger and cargo aircraft.

The adoption of the standard has been discussed during recent ICAO DGP meetings, though no firm decision has been made to date. The DGP recognizes that the standard will need to be evaluated to determine whether it provides an acceptable level of safety before agreeing to implement it. The decision on how the standard is to be adopted will not be taken until the standard is complete. In the meantime, the DGP has held preliminary discussions on how to implement it. The discussions generally centered on marking, labelling, and the need for traceability. During a previous meeting, the following points were raised:

a) A mark on the package to indicate which specific test the battery/cell/packaging combination had passed would be necessary.
b) Provisions were being proposed as part of the SAE standard for cells and batteries to be shipped at a tested state of charge in any type of packaging if the cells or batteries did not produce hazardous consequences when tested unpackaged – these are referred to as “benign” cells and batteries. If adopted, a specific mark on the package would be needed to indicate that such cells or batteries were contained within.
c) An indication of the State under which the package was approved would need to be marked on the package, like what is already required for UN-tested packaging.
d) Requiring additional information be communicated to the operator to indicate the degree of risk and certify that the package had passed the test and was in full compliance with the regulations. One suggestion was for the test summary to accompany the package.

e) Concerns were expressed about operator requirements, recognizing that the operator was limited to looking only at the documentation, the package, and its markings.
f) An opinion that the existing framework for dangerous goods transport was enough, and that no additional requirements would be necessary, was expressed.

An issue of interest to the aviation industry is the threat of an external fire on packages of lithium batteries in an aircraft cargo hold. There are mixed views on whether the threat needs to be considered in the standard. An external fire sub-group has been established to consider the threat and recommend a course of action. The baseline test and a range of supplemental tests are being developed to cover different battery sizes, cell configurations, and packagings that could be used. These tests address the hazards posed by a single cell within a packaging going into thermal runaway, but do not address the effects from an external fire. Separate tests are therefore being developed to address the effects from an external flame and heat on lithium cells or batteries.

Since its start, the SAE G-27 has made progress in developing the ""Performance Based Package Standard for Lithium Batteries as Cargo on Aircraft" (AS6413)." While the progress has been slow, the standard does provide a baseline test methodology that has impacted current day packaging. For instance, several companies have since applied and been granted approvals to transport batteries at state of charge (SOC) greater than 30% SOC in packagings that pass the proposed G-27 criteria. Additionally, the development of the standard has incentivized companies to test their batteries as offered for transport to better understand whether their packaging can contain the hazardous effects of an initiated thermal event and whether initiating a single cell in a packaging or battery pack leads to propagation. The committee provides a forum for the exchange of technical information related to lithium battery packaging for transportation by air.

UN Working Group on Hazard-Based Classification of Lithium Batteries and Cells

The United Nations (UN) Transport of Dangerous Goods Sub-Committee has undertaken an initiative to classify lithium batteries based on their inherent hazards. This means manufacturers of lithium batteries will need to test batteries to failure to assess the hazards they pose during thermal runaway. The eventual objective is to gather failure data on all lithium cells and batteries. This will be a very difficult task given that cells and batteries differ wildly in terms of chemistry, form factor, energy content, pack design, safety features, and material of construction. The initiative is aimed at establishing test methods and criteria by which lithium batteries can be more effectively regulated based on whether they propagate as well as the hazards they pose based on a measurement of the gas evolved, the amount of heat, and presence of flames. The goal of destructive testing is to determine what happens when a given cell or battery goes into thermal runaway. Some batteries are more resistant to thermal runaway, but generally they release the same chemicals with the same level of toxicity and potential flammability. Many companies resist testing batteries because the information could potentially be used in civil liability cases and because they do not want the information to become public. The work of the UN Working Group should result in creating greater transparency in the market, thus improving quality and safety of lithium batteries.

The nine categories of hazards that the UN Working Group is currently considering include:

A. Benign hazard
B. High temperature hazard
C. Gas hazard
D. High temperature and gas hazard
E. High temperature and gas hazard with the presence of flames
F. Propagation and high temperature hazard
G. Propagation, high temperature and gas hazard
H. Propagation, high temperature and gas hazard with the presence of flames
I. Propagation, violent reaction, high temperature and gas hazard with the presence of flames

The thermal propagation test proposed is a thermal abuse is partly based on the test method of SAE AS6413 standard. The flow chart (Figure 10) below shows possible classification outcomes based on identified hazards.

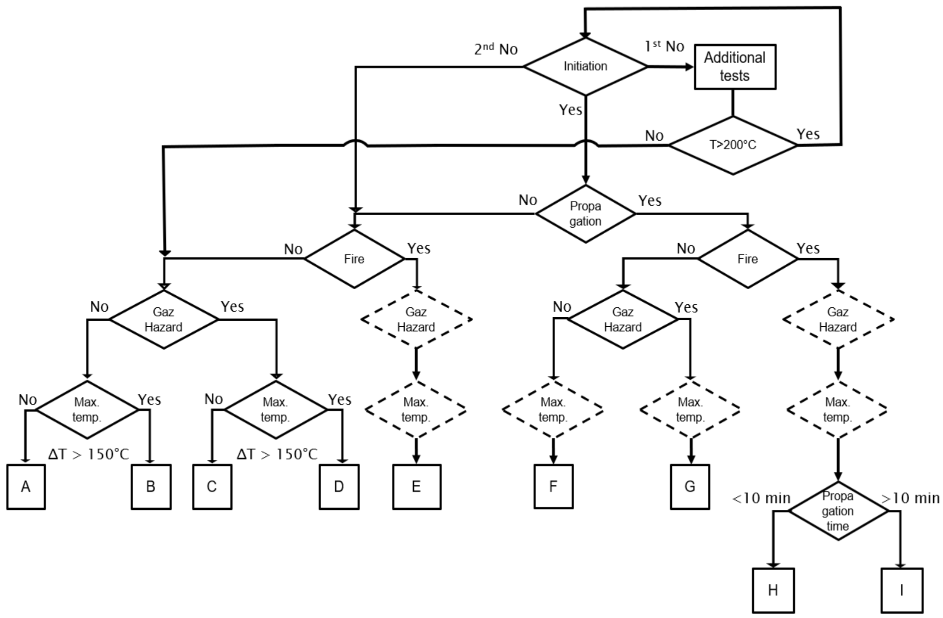

Figure 10
Proposed Classification Flow Chart

The ultimate goal of dangerous goods regulations is to enhance transportation safety. At present, the primary way regulators protect against lithium cell and battery hazards is through inspection of companies shipping lithium batteries, enforcement of mandatory UN 38.3 testing, packaging, quantity limits, Watt-hour and lithium metal content limits, as applicable, state of charge restrictions on lithium ion cells and batteries, and segregation (from other dangerous goods) requirements. This method has proven effective thus far, but, as with all dangerous goods, regulators must follow the philosophical approach of (1) understand the hazards, and (2) set transport conditions accordingly. In our current moment, the first step of the approach is incomplete which means that the second step is imperfect. Because safety is the goal, whether enhancements in safety come through packaging or safer cell and battery technologies is irrelevant. Though packaging may play an important role in the UN Working Group's effort, it must be noted that developments in safe battery technology may be the ultimate driver of enhancements in lithium battery safety – in both use and transportation. As such, PHMSA must stay connected to the work of the UN body on this issue to gain a better understanding of current cell/battery hazards and future improvements in safe cell/battery technologies.

Once hazards are better understood, the idea at the core of this project is to incentivize cell and battery manufacturers to utilize safer cells and batteries. The outcome of this re-classification effort may be that cells and batteries that pose minimal hazard are provided significant regulatory relief (e.g., modest packaging and hazard communication requirements) while more volatile cells and batteries are subject to extremely restrictive transportation regulations (e.g., fire-resistant packaging, SOC limits, strict quantity limits, full hazard communication, and shipping papers). The Working Group on this matter remains active, though formal recommendations and subsequent regulatory changes are not expected for at least two to four years.

Advancements in Fire-Resistant Lithium Battery Packaging

Both the SAE G-27 and the UN Informal Working Group have inspired packaging companies to develop innovative packaging solutions that enhance safety. The innovations use various technological solutions and packaging design features to minimize risk and contain thermal effects. Examples include the use of heating insulating materials such as:

a) Alkaline earth silicate (AES) fiber wool which is a man-made vitreous fiber (MMVF), high temperature insulation wool (HTIW), amorphous mineral fiber wool (AMFW), Calcium - magnesium - silicate fiber (CMS), Synthetic vitreous fiber (SVF);
b) FlameBlock® panels, LP's proprietary non-combustible, fiberglass-reinforced Pyrotite® treatment is added, which combines flame-spread and burn-through resistance;
c) Intumescent coatings applied to fiberboard;
d) Robust steel or aluminum boxes;
e) Foil thermally lined packages utilizing a proprietary fire and heat mitigating material;
f) Pastes or gels that have excellent heat barrier capabilities such as FireIce® Medium Term Retardant Gels; and
g) Use of heat and smoke absorbing materials such as mineral-based extinguishing agents composed of non-crystalline glass granulates as demonstrated by CellBlockEX.

Thus far, the innovative solutions mentioned above have primarily been used to reduce the risk of transporting damaged/defective batteries, lithium ion batteries over 30% state of charge, large quantities of batteries destined for recycling, or recalled lithium ion or metal batteries. The expense of such packaging combined with the limited risk presented by lithium ion batteries at < 30% SOC has reduced the extent to which innovative, fire-resistant packaging is used for normal shipments of lithium ion cells and batteries. Investments in modern packaging options that provide flame retardance and arrestment, thermal management, pressure management, blast containment, and gas and smoke filtration is an industry best practice, but has not been widely adopted.

Battery Design and Manufacturing Innovation

Improvements in lithium battery design, chemistry, and manufacturing processes are in progress, though the reality is that higher energy content and longer life have outweighed the pursuit of improved safety. Universities, government labs, and lithium battery manufacturers are all racing to find the next innovation that will make lithium batteries safer and less volatile.[29] Experts agree that while billions of dollars are continuing to be invested in the search for safer, longer lasting, and higher energy density batteries, it is difficult to see lithium-ion based batteries being replaced anytime soon.[30] The focus for safety improvement is based on the following potential safety enhancement approaches:

- Improving the anode and cathode materials;
- Improving or replacing the electrolyte; and
- Designing battery packs with passive propagation resistance (PPR) to reduce the likelihood of cell to cell propagation.

The need for robust packaging may not be as critical if the cells and batteries themselves are designed to be less likely to experience thermal events and, if they do, the reaction volatility is minimized. While progress is being made across several areas, it will be a time-consuming process and not all applications will be able to take advantage of the safety innovations. Therefore, a continued approach to ensure appropriate packaging

[29] Golden, Mark. New Coating Developed by Stanford Researchers Brings Lithium Metal Battery Closer to Reality. Stanford News Service. August 26, 2019.

[30] Lithium-ion Overcomes Limitations, New battery protection for portable electronics cuts manufacturing steps and costs, Power Electronics, DEC 21, 2017, https://www.powerelectronics.com/technologies/power-management/article/21864070/lithiumion-overcomes-limitations

that can mitigate the risks is prudent until such time that cells and battery designs and manufacturing processes are improved.

Anode and Cathode Enhancements

Lithium-ion batteries have both a cathode (positive electrode), an anode (negative electrode) and electrolyte as conductor. The cathode is generally a metal oxide and the anode is typically made of porous carbon. Research is ongoing to explore and assess the use of various alternative materials. For example, scientists have been experimenting with using silicon nanoparticles for the anode instead of commonly used carbon graphite or using solid electrolytes instead of liquid ones. Researchers are working on improving the energy density (energy per weight and volume), the price, safety, environmental impact, and even the lifetime of the most popular lithium-ion batteries, as well as designing new types. The traditional graphite anode lattice could be replaced with silicon, which holds ten times as many lithium ions, though silicon tends to expand as it absorbs lithium, so batteries will have to account for that to ensure safe use. Unfortunately, not all technological battery breakthroughs will result in safer batteries as there is a constant struggle between performance and safety.

Electrolyte

Lithium ion batteries are made up of an anode, a cathode, a separator, an electrolyte, a positive current, and a negative current. The anode and cathode are the "ends" of the battery; a charge is generated and stored when the lithium ions (carried by the electrolyte) move between the two ends of the battery. The electrolyte is where the charged particles flow. Certain solid materials, like copper selenide, will also allow ions to flow, but not quickly enough to run high-powered devices.[31] However, significant progress is being made in identifying solid electrolytes where the charged particles can move as fast or faster than they do through liquid electrolyte. The potential safety benefits of solid electrolytes are significant because if a current lithium-ion battery is damaged, the battery shorts and heats up, the liquid vaporizes, and then nothing is there to prevent a rapid discharge of energy, resulting in a thermal event. Most liquid electrolytes are flammable and serve as fuel in a thermal event contributing to the evolution of flammable gases. A solid electrolyte will prevent that short circuit and the full-metal anode will enhance safety by removing the flammable fuel. Additionally, over repeated cycles, liquid electrolytes begin to dissolve the cathode and anode, and this is a known cause of battery failure.

Passive Propagation Resistance (PPR)

Propagation resistance is ideally achieved by use of passive features integrated into the battery pack design – collectively referred to as passive propagation resistance (PPR). Effective PPR requires mechanisms to manage the heat released from the initial cell failure in order to prevent overheating of adjacent cells. Such mechanisms include:

- Inhibiting heat conduction
- Removing residual heat from the carcass of the failed cell
- Managing ejecta (flame and superheated cell contents)

PPR characteristics are best incorporated in battery design from the outset, rather than as a retrofit. Additionally, due to the complexity and inherent variability in failure modes during cell thermal runaway, testing is required to evaluate and ultimately validate the safety of battery designs.

[31] Charging Ahead: The Future of Batteries, Smithsonian Magazine, Nathan Hurst, March 7, 2017.

There has been significant work to study the design of batteries to reduce the likelihood of cell-to-cell propagation in lithium batteries. The SAE G-27 Committee and UN Lithium Battery Working Group have recognized this as a promising initiative to reduce risk in transportation. There are different approaches to addressing PPR; one of the most promising is designing cells that are less volatile. Cells are the building blocks for battery designs. There has been recent focus on cells that react less violently and do not fail in a way that results in a significant amount of "ejecta" being released. Ejecta is the term for the hot particles that are expelled when a cell experiences thermal runaway. Cells that do not experience side wall ruptures are less likely to present ejecta and cause propagation to neighboring cells in a battery pack. Approaches to enhancing battery safety and promoting PPR include:

- Providing adequate cell spacing & heat dissipation;
- Including thermal shields between cells to minimize cell to cells propagation; and
- Introducing fire suppression materials in battery packs to minimize propagation.

RECOMMENDATIONS

Due to their reliability and affordability, lithium batteries are ubiquitous in modern life, powering everything from small electronics to electric vehicles. With increasing demand for energy storage in various applications, the prevalence of lithium batteries will increase in coming years and decades. As previously detailed, lithium cells and batteries pose serious hazards in the rare occurrence of failure, including extreme heat, flame, projectile, and emission of toxic and flammable gases. As a result, it is vital that transportation regulatory agencies continue their focus on the safe transport of lithium batteries, especially the air mode as that is the most vulnerable to a catastrophic lithium battery incident. Based on our study of current lithium battery packaging practices and lithium battery safety initiatives, we offer the following recommendations to PHMSA:

1. *Clarify Inner Packaging Requirements for Lithium Batteries*

   The inner packaging requirements of 49 CFR §173.185(b)(3) are unclear. The requirements state that "lithium cells or batteries must be placed in non-metallic inner packagings that completely enclose the cells or batteries, and separate the cells or batteries from contact with equipment, other devices, or conductive materials (e.g., metal) in the packaging." Some shippers interpret this to mean that each individual cell or battery must be completely enclosed, while others interpret it to mean they can place multiple cells or batteries inside of a single enclosure such as trays, dividers or blister packs.

   The regulations need clarification on what constitutes an inner packaging (i.e., are dividers or trays fulfilling inner packaging requirements?). There are disparities between the packaging requirements in the HMR and UN Model Regulations. For instance, PHMSA acknowledged in a proposal to the UN TDG Sub-Committee[32] that:

   > "there are varying interpretations in the application of P903 as it relates to inner packaging and protection of lithium cells and batteries even amongst competent authorities. Packing instruction P903 indicates the need for cells and batteries to be protected from short circuits and damage caused by the movement or placement of the cells or batteries within the packaging. However, there are no requirements in packing instruction P903 for the use of inner packagings, or other indication of how the cells or batteries are intended to be protected from short circuits. A clear indication of appropriate inner packaging or other protection is critical to ensure safety related to handling in transport."

   Based on responses to PHMSA's proposal, many Competent Authorities have differing views on inner packaging requirements. In lieu of proposing text here, we recommend PHMSA align HMR requirements with the decision taken on this issue at the UN TDG Subcommittee meeting. This regulatory alignment can be included in PHMSA's next international harmonization rulemaking. It is the opinion of the authors of this study that trays and dividers that are configured to enclose and protect the batteries from short circuits and damage caused by the movement within the packaging should be sufficient. The definition for "inner packaging" is vague; "*Inner packaging* means a packaging

---

[32] *ST/SG/AC.10/C.3/2020/56, submitted by the Expert from The United States, April 16, 2020*

for which an outer packaging is required for transport." Changing the definition of inner packaging may not solve the problem and could result in other unexpected consequences for other shipments of hazardous materials. Instead, we recommend not solely relying on inner packaging, but to amend the regulations to clearly indicate that inner packagings, closed trays, or dividers are acceptable provided batteries are protected from damage and short circuit.

2. *Maintain the Current 30% State of Charge Limitation Until SAE G-27 and/or UN WG is Complete*

It has been demonstrated that the hazards of a lithium ion cell or battery thermal runaway are lessened as the state of charge of the cell or battery is reduced. At present, there is no justification to mandate more robust packaging for air transport of UN 38.3-tested, non-damaged lithium ion cells and batteries because the likelihood of a thermal runaway is extremely low, and the cells and batteries must be transported at 30% SOC or less. There remain concerns regarding the difficulties in verifying and enforcing SOC limits, but this issue is better addressed through targeted outreach and enforcement of non-compliant shippers rather than further restricting compliant shippers. PHMSA should engage in collecting data on various lithium battery chemistries, form factors, and designs to confirm that the 30% SOC limit provides an appropriate reduction in risk for all types of cells and batteries.

The time to consider amending the SOC limitation will be upon completion of the UN Working Group (WG) on Hazard-Based Classification of Lithium Batteries and Cells, or the completion and adoption of the SAE G-27 Lithium Battery Packaging standard. The results of the UN WG will likely show a more granular level of hazards to which transportation regulatory authorities can set specific parameters based on the hazards of a given cell or battery. With that said, it is expected that the SAE G-27 standard will be completed ahead of the UN WG. The 30% SOC restriction has thus far proven to be an effective safety measure and, while there are objections, it has been widely implemented throughout the supply chain by shippers. We recognize that in some instances there is a need to ship batteries at higher states of charge. This is currently authorized under an approval and PHMSA has issued such approvals (e.g. CA2016030004). Should the requirements resulting from the SAE G-27 standard become regulation, it is our recommendation that shippers be required to use a certified G-27 package only in the case where they are shipping a lithium ion cell or battery at an SOC exceeding 30%, or if shipping their cells or batteries as cargo aboard a passenger aircraft.

3. *Focus on Multi-Layered Safety Approach*

Packaging is not the only mechanism available to enhance the safe air transport of lithium batteries. The requirements for the transport of lithium batteries are based on risk and are designed to work together to create layers of safety. There are other actions available, including increased enforcement against non-compliant shippers, fire resistant Unit Load Devices (ULD), better acceptance procedures, safer battery technologies, quality assurance sampling, limiting external aggressors (e.g., high heat or impact) during loading and flight, fire detection and suppression systems, cargo segregation, and cell/battery manufacturing quality program. IATA has highlighted the Bowtie Risk Analysis[33] developed by the United Kingdom's Civil Aviation Authority (CAA) as an example of a multi-layered approach. In addition, IATA publishes a Lithium Battery Risk Assessment Guidance for Operators[34] that details how air carriers can minimize risks posed by lithium batteries via a multi-layered approach. PHMSA and FAA

---

[33] *Sample of Bowtie Risk Analysis Model for the Carriage of Lithium Batteries on Cargo Aircraft. Prepared by the UK Civil Aviation Authority.* *https://www.iata.org/contentassets/05e6d8742b0047259bf3a700bc9d42b9/ukca_-bowtie_model_carriage_of_lithium_batteries.pdf*

[34] *Lithium Battery Risk Assessment Guidance for Operators – 3rd Edition. Presented by the International Air Transport Association (IATA). 16 March 2020.*

have long recognized that the challenges associated with the transport of lithium batteries by air can only be solved by applying a multi-layered approach. PHMSA should further evaluate the various initiatives that can contribute to reducing the risk of shipping lithium batteries as cargo aboard aircraft, including what other Competent Authorities are doing in this area, and encourage these multi-layered approaches through outreach or the adoption of a safety management system programs.

4. *Transporting Lithium Cells and Batteries in Sealed Outer Packagings*

As illustrated in this report, most lithium cells and batteries are transported in fiberboard boxes. While such a box does not offer much in terms of thermal resistance, it is not airtight. Off-gases produced by a thermal event will likely escape the outer package under a minimal amount of internal pressure. On the other hand, sealed packages (e.g., drums) may pose a concern. Sealed drums are not a common outer packaging used for air shipments of batteries (they are more common for highway, rail, and ocean shipments of used batteries, however), but they are used for shipments of prototype cells and batteries in accordance with DOT SP 20323, for instance. In the case of a thermal event, the build-up of gases inside the sealed container presents a significant explosive hazard. The packaging requirements in 49 CFR §173.185 do not address a requirement to prevent pressure buildup within a package containing lithium batteries. The regulations and pertinent special permits should address the fact that a sealed container may need to provide venting to prevent an overpressure situation or the creation of a flammable atmosphere within the package that could ignite in a violent reaction. Along these lines, PHMSA should review all Special Permits and Approvals that apply to air transport of lithium batteries to assess authorized packaging and, if necessary, update packaging requirements on those Permits or Approvals. PHMSA should review all special permits and approvals issued that authorize the transport of prototype batteries as cargo aboard aircraft for consistency and to determine if an adequate level of safety is afforded.

5. Interagency Task Force on Cooperative Safety Efforts, Information Exchange, and Coordination

PHMSA should revitalize their interagency working group on lithium battery safety and meet monthly. The Lithium Battery Inter-Agency Coordination Group that PHMSA helped organize has ceased to meet regularly. The FAA Reauthorization Act of 2018 mandated DOT to work with other Federal agencies and establish a lithium battery safety working group to promote and coordinate efforts related to the promotion of the safe manufacture, use, and transportation of lithium batteries and cells (see FAA Reauthorization Act text below).

> *LITHIUM BATTERY SAFETY WORKING GROUP.*
> *(1) IN GENERAL.—Not later than 90 days after the date of enactment of this Act, the Secretary of Transportation shall establish a lithium battery safety working group (referred to as the ''working group'' in this section) to promote and coordinate efforts related to the promotion of the safe manufacture, use, and transportation of lithium batteries and cells.*
> *(2) DUTIES.—The working group shall coordinate and facilitate the transfer of knowledge and expertise among the following Federal agencies:*
> *(A) The Department of Transportation.*
> *(B) The Consumer Product Safety Commission.*
> *(C) The National Institute on Standards and Technology.*
> *(D) The Food and Drug Administration.*
> *(3) MEMBERS.—The Secretary shall appoint not more than 8 members to the working group with expertise in the safe manufacture, use, or transportation of lithium batteries and cells.*

DOT should comply with the Congressionally mandated requirement to establish the Lithium Battery Safety Working Group.

6. *Lithium Battery Training*

PHMSA's International Standards Coordinator should submit a proposal to the UN Transport of Dangerous Goods Sub-Committee to propose to add a requirement in Special Provision 188 of the UN Model Regulations for "Adequate Instruction" training. Mandating employee training, including how to safely package lithium batteries, is an essential component for ensuring the safe transport of dangerous goods. The proposed training should stipulate that the employer must:

- Identify the different configurations of lithium batteries that they ship, i.e. lithium batteries and/or lithium batteries packed with equipment and/or lithium batteries contained in equipment; lithium metal batteries and/or lithium ion batteries;
- Make employees aware of differences in modal requirements such as understanding the additional restrictions that apply for air transport (e.g. restrictions for passenger aircraft, 30% State of charge);
- Document the procedures that apply to the configurations and battery types that they ship;
- Maintain a record that identifies each applicable employee and the date(s) that this instruction was provided.
- Provide employees with periodic refresher, or at least demonstrate that they remain "adequately" instructed on how to perform their assigned tasks. This should be done at least every two years or whenever the procedure is revised, or regulations are changed, whichever is sooner.
- Ensure that companies that are involved in reverse logistics, i.e. arranging for returns of lithium batteries, lithium batteries packed with equipment or lithium batteries contained in equipment develop a clear instruction for consumers on the process to be followed for returning products.

7. *Outreach and Enforcement*

DOT should implement and coordinate with other Competent Authorities to enhance outreach and enforcement as mandated under the FAA Reauthorization Act.

> *COOPERATIVE EFFORTS.—The cooperative efforts the Secretary shall carry out the following:*
> *(A) Encouraging training programs at locations outside the United States from which substantial cargo shipments of lithium ion or lithium metal batteries originate for manufacturers, freight forwarders, and other shippers and potential shippers of lithium ion and lithium metal batteries.*
> *(B) Working with Federal, regional, and international transportation agencies to ensure enforcement of U.S. Hazardous Materials Regulations and ICAO Technical Instructions with respect to shippers who offer noncompliant shipments of lithium ion and lithium metal batteries.*
> *(C) Sharing information, as appropriate, with Federal, regional, and international transportation agencies regarding noncompliant shipments.*
> *(D) Pursuing a joint effort with the international aviation community to develop a process to obtain assurances that appropriate enforcement actions are taken to reduce the likelihood of noncompliant shipments, especially with respect to jurisdictions in which enforcement activities historically have been limited.*

(E) Providing information in brochures and on the internet in appropriate foreign languages and dialects that describes the actions required to comply with U.S. Hazardous Materials Regulations and ICAO Technical Instructions.

(F) Developing joint efforts with the international aviation community to promote a better understanding of the requirements of and methods of compliance with U.S. Hazardous Materials Regulations and ICAO Technical Instructions.

8. *Consider Mechanisms to Evaluate Probability of Lithium Battery Failure in Transport*

To truly mitigate the risks involved in transporting lithium batteries, it is critical to evaluate both sides of the risk equation: Probability and Consequence. Failure testing of batteries and package testing focuses on the consequence factor of the risk equation. Many responsible battery manufacturers are spending resources to ensure that their batteries are protected against short circuit and are conducting extensive research on new methods to stabilize the chemistry of batteries, including solid-state electrolytes.

PHMSA and other global regulators of lithium battery safety should consider mechanisms to quantitatively evaluate the probability of lithium battery failure in transport. There would be an appreciable effect on safety if companies were encouraged to engineer improved safety into their products to mitigate the risk of failure in transport by significantly reducing or eliminating the probability of failure. Regulators could consider a testing regime like MIL-STD-810G, which is a series of tests designed to put equipment through extreme environmental, transport, and use conditions. Batteries and equipment that have been proved to withstand these types of tests would be allowed regulatory relief because they have demonstrated that the probability of failure is minimal. Batteries and equipment that have not been tested in this series of tests would need to be transported with higher regulatory standards, including more robust packaging and restrictions for air transport. PHMSA should consider further research in quantifying probability of varied lithium battery chemistries, configurations, and safeguards.

9. *Increase Participation on SAE G-27 Lithium Battery Packaging Committee*

We encourage PHMSA to put more effort in trying to bring the SAE G-27 standard to completion. The Committee has been developing this standard for more than four years and has been significantly slowed down by overly specific proposals, inability to compromise, and a deep reluctance to implement performance-oriented solutions. With more active participation, PHMSA may be better equipped to facilitate compromises among various factions of the Committee based on their experiences and long history of successfully brokering compromise agreements within various regulatory bodies (UN Transport of Dangerous Goods Sub-Committee and ICAO Dangerous Goods Panel).

10. *Improve Lithium Battery Shipping and Incident Data Gathering Efforts*

Though this report details a few places where lithium battery shipping volumes are detailed, there remain large gaps and a lack of granularity in these data. Without shipping data, assessing risk becomes a difficult task. Further, though incident data is collected through the PHMSA 5800.1 form as well as by the FAA, oftentimes the incident report information lacks detail needed to understand the root cause of the incident. More granular information on incidents will allow regulators to uncover trends in causality that may point to issues with quality of manufacturing, inadequate packaging, counterfeit products, or exposure to extreme conditions such as high heat or significant mechanical damage during handling.

To address these data concerns, it is recommended that PHMSA leverage the on-going work of the recently established Lithium Battery Air Safety Advisory Committee that was established under Section 333(d) of the FAA Reauthorization Act of 2018 (Public Law 115-254). This Act mandated the Secretary of Transportation (the Secretary) to establish a committee composed of representatives of the Federal Government and representatives of lithium battery and product manufacturing industries, air carriers, and shippers, among other industries. This committee has established 4 subcommittees, one of which will assess lithium battery data collection. The data collection subcommittee provides PHMSA an opportunity to partner with industry stakeholders to gather better data. This is vital because PHMSA is dependent on industry reporting to gather quality data. By actively working with leading industry representatives across various sectors, PHMSA may be able to gather better data on shipping volumes, incidents, and root causes of battery failures.

11. *Continue to Support Efforts of UN Working Group on Hazard-Based Classification*

The lithium battery industry is more focused on enhancing safety through battery design, chemistry, and internal safety features than through enhanced packaging. The incentives to develop safe battery technologies are powerful because, unlike packaging, which is only applicable for transportation, reducing hazards associated with the battery will improve safety throughout the its life cycle, including during transportation, storage, charging, and use. Because PHMSA is limited to transportation, it is difficult for the agency to dictate specific chemistries, design, and manufacturing practices directly. However, the agency can incentivize the production and use of safer cells and batteries by making them less burdensome to transport through regulatory relief. This is the goal of the UN Working Group on Hazard-Based Classification of Lithium Batteries and Cells. It is recommended that PHMSA continue their support of this effort. Though the results of this group will likely not be realized for years, the safety benefits of a hazard-based classification system will be immense. It is recommended that PHMSA not only participate, but take an active role in the effort, particularly in partnering with or incentivizing various cell or battery manufacturers to conduct failure analysis. Currently, the bottleneck of the UN WG project is a lack of cell and battery failure test data. Industry is often reluctant to participate due to financial and confidentiality reasons. To remove such concerns, PHMSA may consider research project grants to drive industry stakeholders to participate in a more active manner.

12. *Outreach Program on Lithium Battery Compliance*

Over the years, the regulations covering the transportation of lithium batteries have become more complicated for shippers to navigate. As a result, many shippers struggle with transportation compliance. To address this, PHMSA should consider an outreach program focused on lithium battery compliance and clarifying common regulatory misunderstandings that compromise safety. A national outreach program should be conducted, and the findings should be summarized and made public through a safety advisory published in the Federal Register. Areas of focus for such a program should be:

- How are packaging manufacturers interpreting selective testing provisions when selling UN Performance Oriented Packages (PoP) and what guidance, including closure instructions, are provided to purchasers of packaging?
  Many suppliers provide closure instructions along with the packaging and they also have closure instructions and UN package test reports (or summaries thereof) on their websites. Providing closure instructions to package users is the minimum requirement. In our experience, packaging manufacturers are extremely reluctant to offer further guidance regarding how a shipper can use their package in ways that vary from how the package was originally tested.

The selective testing provisions are complex and difficult for many packaging manufacturers to understand. Although the definitions of "different packaging" and the packaging variations are detailed in 49 CFR §178.603, packaging suppliers do not want to take on additional responsibility for the shipment by providing interpretative guidance to their customers. This is understandable given the complexities that come with interpreting whether a specific change constitutes a "different packaging" or meets the conditions of a variation. Understanding that suppliers are unwilling to sign off on packaging changes made by the shipper, it may be helpful to provide further guidance on proper use of packaging variations. As it stands now, a supplier may point to 49 CFR §178.603, but the regulatory text of this section is difficult for a non-expert to navigate confidently. The suggested guidance can remain general in nature yet still provide a better explanation of the flexibility that variations give to shippers of hazardous materials.

- What packaging buyers use as guidance when deciding what packaging to select?
  Most reputable packaging vendors provide technical support for their customers, but this is not always the case. Even with customer support, packaging suppliers are still reluctant to offer definitive stances on the end use of packaging, which explains the packaging disclaimers on most closure instructions and/or UN test reports available to customers. Without this guidance, packaging buyers lean on packaging specifications (ECT, Mullen for non-specification fiberboard) and the UN packaging mark information (e.g., UN 4G/X25/S/…).

- What violations are being cited by regulators? What information would reduce the regulatory non-compliance?
  According to PHMSA annual civil penalty reports published since 2016, there have been remarkably few penalties assessed against non-compliant shippers of lithium batteries. Of the settled cases, many were the result of shippers offering undeclared packages containing lithium batteries. There were, however, a few cases where shippers failed to use appropriate packaging for these shipments. For example, there were three cases where PHMSA assessed penalties against a shipper for using an outer packaging that was not UN-rated or the outer packaging had not been periodically retested (Case Numbers: 07-0130-SB-EA, 18T-0176-SH-EA, 18-0253-SH-WE).

  Unfortunately, FAA enforcement data lacks details about a specific case. When reviewing the FAA Press Releases for announced penalties that have not yet been settled, we came across a few instances where FAA cited lithium battery shippers for failure to comply with packagings regulations. In many of the enforcement cases, shippers were cited for improper inner packagings, specifically that they failed to prevent batteries from possible short circuit by packing them loose and unprotected in outer packagings and, in some cases, passenger luggage.

- What training details should be included by companies to ensure regulatory compliance?
  Regarding packaging, training courses should apply more focus on how to meet the inner packaging requirements. As detailed in this report, inner packaging requirements are vague (e.g., interpretation of completely enclosed, proper cushioning, securing against movement) and often result in confusion among shippers. Getting the inner packaging right is vital as that is the primary method to protect against short circuit. To aid companies in training their employees, PHMSA should consider updating their *Shipping Batteries Safety By Air: What You*

Need to Know[35] guidance document. The document provides some useful information but must be updated to reflect recent regulatory changes and could benefit from adding more detailed information about inner and outer packaging requirements.

- What industry best practices could be better advocated?
  For small lithium batteries, UN Performance packaging is not required. As a result, most lithium cells and batteries are shipped in non-specification packages, typically fiberboard. Companies using packaging that has been successfully tested to applicable ASTM and ISTA represents an industry best practice that can be better communicated. In addition, many companies are uncertain about the 1.2-meter drop test requirement for non-specification packages intended to contain lithium batteries. The regulations do not specify the way these tests must be performed and do not offer a test procedure. This results in confusion among shippers and packaging suppliers, with some performing these tests in accordance with the drop test requirements of §178.603 and others forgoing the test altogether because they can justify a package is *capable* of withstanding the drop test based on package specifications, shipping history, or other factors. Though we do not advocate converting the existing performance-based 1.2-meter drop test into a prescriptive test along the lines of §178.603, it is our recommendation that PHMSA could offer guidance for shippers on acceptable means to meet the 1.2-meter drop test requirement.

13. *External Fire on SAE G-27 Committee*

The impact of external fires on packaged lithium batteries remain a significant concern of regulators and carriers. PHMSA should conduct further research to determine the frequency of external fires in air transportation and how to mitigate this concern. For example, should high-energy lithium batteries be shipped within a fire-proof box? At what energy or level should more robust packaging be required to protect the battery from external fire?

[35] https://www.phmsa.dot.gov/safe-travel/shipping-batteries-safely-air-what-you-need-know

APPENDIX A: SUMMARY OF CURRENT REGULATIONS

UN3480 LITHIUM ION BATTERIES

	Section IA	Section IB	Section II
Energy Content	Each Cell: > 20 Wh Each Battery: > 100 Wh	Each Cell: ≤ 20 Wh Each Battery: ≤ 100 Wh	Each Cell: ≤ 20 Wh Each Battery: ≤ 100 Wh
Net Weight Limit	35 kg (if exceeding 35 kg, must obtain government approval)	10 kg (if exceeding 10 kg, ship Section IA)	N/A *No more than 1 package/consignment
Max Cells/Batts Per Package	N/A	N/A	Max: 2 batteries or 8 cells (if exceeding 2 batts or 8 cells, ship Section IB)
UN 38.3 Tests	Yes	Yes	Yes
Cell/Battery State of Charge	≤ 30% of its rated capacity	≤ 30% of its rated capacity	≤ 30% of its rated capacity
Inner Packaging	Cells/batteries completely enclosed in inner packaging	Cells/batteries completely enclosed in inner packaging	Cells/batteries completely enclosed in inner packaging
Outer Packaging	UN Performance Package Required Box: 4A, 4B, 4C1, 4C2, 4D, 4F, 4G, 4H2, 4N Jerrican: 3A2, 3B2, 3H2 Drum: 1A2, 1B2, 1D, 1G, 1H2, 1N2 *for > 12kg, protective enclosure allowed	Strong, rigid outer packaging capable of withstanding 1.2 m drop test	Strong, rigid outer packaging capable of withstanding 1.2 m drop test
Package Marks/Labels	 **UN3480** **Lithium Ion Batteries** **Net Qty: X.X kg**	 **UN3480** **Lithium Ion Batteries** **Net Qty: X.X kg**	
Shipper's Declaration	Required	Required	Not Required
Aircraft Type	Cargo Aircraft Only	Cargo Aircraft Only	Cargo Aircraft Only

UN3090 LITHIUM METAL BATTERIES

	Section IA	Section IB	Section II
Energy Content	Each Cell: > 1.0 g lithium Each Battery: > 2.0 g lithium	Each Cell: ≤ 1.0 g lithium Each Battery: ≤ 2.0 g lithium	Each Cell: ≤ 1.0 g lithium Each Battery: ≤ 2.0 g lithium
Net Weight Limit	35 kg (if exceeding 35 kg, must obtain government approval)	2.5 kg (if exceeding 2.5 kg, ship Section IA)	N/A *No more than 1 package/consignment
Max Cells/Batts Per Package	N/A	N/A	Max: 2 batteries or 8 cells (if exceeding 2 batts or 8 cells, ship Section IB)
UN 38.3 Tests	Yes	Yes	Yes
Cell/Battery State of Charge	Not Applicable	Not Applicable	Not Applicable
Inner Packaging	Cells/batteries completely enclosed in inner packaging	Cells/batteries completely enclosed in inner packaging	Cells/batteries completely enclosed in inner packaging
Outer Packaging	UN Performance Package Required Box: 4A, 4B, 4C1, 4C2, 4D, 4F, 4G, 4H2, 4N Jerrican: 3A2, 3B2, 3H2 Drum: 1A2, 1B2, 1D, 1G, 1H2, 1N2	Strong, rigid outer packaging capable of withstanding 1.2 m drop test	Strong, rigid outer packaging capable of withstanding1.2 m drop test
Package Marks/Labels	 **UN3090** **Lithium Metal Batteries** **Net Qty: X.X kg**	 **UN3090** **Lithium Metal Batteries** **Net Qty: X.X kg**	
Shipper's Declaration	Required	Required	Not Required
Aircraft Type	Cargo Aircraft Only	Cargo Aircraft Only	Cargo Aircraft Only