Lithium Battery Transport Research Program: review of environmental conditions during freight transportation

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Review of Environmental Conditions during Freight Transportation

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LIST OF ACRONYMS

ALPA	Air Line Pilots Association
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DHL	Originally standing for (D)alsey, (H)illblom and (L)ynn
FAA	Federal Aviation Administration
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICCAIA	Council of Aerospace Industries Associations
OCV	Open Circuit Voltage
PD	Power Density
NO_x	Oxides of Nitrogen
SMS	Safety Management Systems
SoC	State of Charge
SO_x	Sulphur Oxides
SRA	Safety Risk Assessment
UN	United Nations
ULD	Unit Load Device
G_{rms}	Root Mean Square Acceleration
VOC	Volatile Organic Compounds

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EXECUTIVE SUMMARY

The number of lithium battery air shipments has increased in the past decade and continues to increase due to increased global demand in many electrical applications. A better understanding of the shipping environment, including the mechanical and environmental stresses experienced during transport, is necessary to help assess the risk posed by lithium batteries during the shipping cycle. This will enable effective risk mitigation strategies for air shipments of products in various segments of the supply chain.

This document includes a literature review of studies regarding 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). This includes analyses of vibration levels, shock levels, humidity levels and temperature fluctuations experienced. Also described are the extreme conditions that packages may be subjected to in transit and the human factors that affect their handling and how they relate to the shipping environment.

Once the shipping environment is defined, it is vital to understand how it affects lithium batteries in order to assess whether or not 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. Therefore, in this study, the extreme conditions that packages may be subjected to during shipping, as reported by previous studies, are compared to the existing tests required by various standards and regulations. All modes of transportation were considered because lithium batteries may be shipped via ground or marine transportation before being transported by air.

Environmental exposures include low pressure (due to altitude), high humidity, temperature extremes and high rates of temperature changes causing stress, air quality and mechanical stress, which includes shock, drop (or fall), vibration, impact and crush. Many standards, including Section 38.3 of the UN Recommendations on the Transport of Dangerous Goods, address the low pressure aspect of air transportation (up to 50,000ft, which is appropriate) [3], [4], [5], [6] and [7]. However, there are no cyclic low pressure tests to simulate lower, more representative altitudes.

High humidity and rain may be an area where battery shipping standards may need to be revised. NRC is not aware of a specific humidity test for battery packaging standards. Also, it may be beneficial to quantify what it means to “fully enclose the cells or batteries” in the IATA packing instructions. Transporting goods from a tropical area by sea and delivering them to cold regions may expose the goods to condensation inside the shipping containers.

The temperature inside shipping containers while waiting to be loaded onto airplanes (which can take hours) at airport tarmacs can reach temperatures higher than 60°C. In fact, at London’s Stansted Airport, temperatures peaked at 37.3°C in the summer of 2003. Furthermore, the temperature on the tarmac in some regions can reach 80°C. The temperature cycling / thermal shock tests, with temperature extremes of -40°C and 85°C, most likely address the expected temperature fluctuations during the transportation cycle. However, some standards only require temperatures up to 70°C, 72°C, or 75°C.

Shock and vibration are the easiest mechanical stress tests to quantify and test by standardized means and were measured in most of the shipping studies reviewed. Shock and vibration are covered in component standards as well as in shipping standards. The package drop test only covers drops of up to 1.2 m. However, some shipping studies found much higher drops (up to 2.15 m) during the shipping cycle. This could be investigated further with new shipping studies as the 1% of occurrences exceeding the 1.26 m drops may not be an acceptable risk for air transportation. Mechanical stress tests from component standards would cover situations where the integrity of the package is compromised (battery free fall, battery impact and crush tests). NRC is not aware of specific tests for some mechanical stress tests, such as vibration, puncture or abrasion and humidity for battery packaging. The current SAE G 27 draft, which addresses packaging testing, only focuses on fire tests.

Air quality, which includes pollution, solid particulates in the air (from combustion) and dust, does not have an effect on well-packed lithium batteries.

Human factors are important as human error has resulted in lithium battery incidents as well as other types of incidents resulting in death. Appropriate, standardized procedures for the safe-handling and transportation of lithium batteries are required to avoid incidents. Procedural oversight and engineering controls can be designed to minimize the potential for serious incident, but ultimately, it is down to the individual if they choose to follow the protocol or not, and incidents may occur as a result.

The new 30% State of Charge (SoC) requirement is difficult to enforce since SoC cannot practically be measured in the field; therefore, this requirement is based on an honour system where shippers are required to declare compliance. Third party factory inspections to verify the use of a reasonable Quality Assurance Program by battery shippers including a protocol to determine SoC would be advisable.

Compliance with Section 38.3 of the UN Tests and Criteria that exists today is self-declaratory and shippers may misreport due to lack of oversight.

There may be gaps in the battery certification and shipping standards that exist today as well as inconsistencies between different standards that require further investigation.

1. INTRODUCTION

The number of lithium battery air shipments has increased over time and continues to increase due to a global expansion of Lithium battery use in many applications. Lithium batteries are shipped by all modes of transportation: ground (truck and rail), marine and air. All transcontinental lithium battery shipments will sequentially use different modes of transportation to get to their final destination, typically starting their transportation cycle by ground followed by air or sea. Upon arrival to their destination port, these shipments then will sequentially be transported by air and/or ground until they reach the consignee.

All modes of transportation subject packages to different environmental conditions such as temperature, humidity and pressure; mechanical stresses such as, crushing, puncture, shock and vibration; which may adversely affect the cargo itself. When it comes to lithium batteries it is important to know the environmental and mechanical stresses to assess how the transportation cycle affects these batteries and thus to understand if the transportation history increases the risk that lithium battery shipments pose to cargo airplanes. Understanding all factors related to all modes of transportation is important to assess the risk of transporting lithium batteries by air; however, information about the mechanical and environmental stresses that may potentially damage packages (or their contents) during shipping is scarce.

There have been a number of incidences of lithium battery failure during transport. The FAA has a list of aviation incidents involving smoke, fire, extreme heat or explosion, related to batteries or battery-powered devices. The 2014 NRC report titled “Lithium Battery Transport Study: Canadian Risk Perspective” classified these incidents. According to this study, out of 136 incidents reported between 1991 and 2013, 64 involved lithium batteries. Twenty of these incidents involved batteries of unknown type and 52 incidents involved batteries with chemistries different from lithium. Out of the 64 lithium battery incidents, 15 involved lithium-metal batteries, 45 involved lithium-ion batteries and 4 were specified as lithium batteries without indicating the type [1]. In most cases it is not possible to assess if the reported incidents were the result of damage occurred during the transportation cycle. In other words, it is not known if the transportation environmental or mechanical stresses triggered the resulting thermal runaway in most cases. In a few incidents it was obvious that the damage that induced the thermal runaway occurred during the transportation cycle (e.g. the battery or device containing the battery was dropped).

In their Air Freight Packaging Pointers, the United Parcel Service of America identified the following list of “normal” hazards which shipments are exposed to [2]:

Environmental Exposures: pressure, humidity, temperature, but also rain, dirt, dust, odors and pollution.

Shipment Handling and Transportation: Shock, Vibration, Puncture, Abrasion and Compression

A literature review of these factors during the transportation cycle was done and is summarized in the following report together with an analysis of how current codes and standards address these issues.

2. ENVIRONMENTAL EXPOSURES

Every mode of transportation exposes packages to the same environmental hazards but at various levels. For example, air transportation exposes packages to the lowest pressure, while marine transportation exposes packages to the highest level of relative humidity for the longest periods of time. Goods are usually tested to ensure they can safely endure the transportation and application environmental conditions. However, gaps may exist between the testing conditions and the actual hazard exposure.

In the following section, we will review the current standards and practices for lithium batteries for each environmental hazard. We will also identify the worst case scenario for each mode of transportation as well as typical air transportation conditions.

2.1. Environmental pressure

The form factor and casing materials matters when we consider challenges related to pressure. For example, cylindrical cells are designed with a pressure relief device to deal with an internal overpressure due to heating and subsequent electrolyte evaporation. Other prismatic form factors may also contain some form of pressure relief design; however, this is not always the situation. Coin cells do not have a pressure relief device. If the internal pressure is high it will bust; if the external pressure is high the coin cell has an internal spring, which can mitigate the effects of some of the pressure differential.

Pressure differential between the environment and the inside of the cell, may have an effect on pouch cells due to the usually soft casing, typically plastic coated aluminum foil. For instance, manufacturing cells at low environmental pressures (e.g. high altitude) and operating at high environmental pressures (e.g. low altitude) would be favourable to the cell mechanical integrity (strong electrode/separator bonding within the winding or z-fold design of the cell). Prismatic cells are closer to pouch cells in terms of form factor but have a rigid casing, which renders them insensitive to environmental pressure. It is important to consider the difference between individual cells vs. cells mounted in a pack or module where the pack or module design may provide external pressure mitigation. In either case, during the cell life cycle there will be a pressure differential between the cell interior and the environment depending on the type of cell, manufacturing process, factory location, and where and how the cells are shipped and used.

Lithium cells are sealed at atmospheric pressure and are tested to resist some pressure differential. Section 38.3 of the UN Recommendations on the Transport of Dangerous Goods has an altitude simulation test in section 38.3.4.1 (termed T.1) [3]. In this test, the cells are stored at 15 to 25^{o}C for 6 hours at a total pressure of 11.6 kPa or less, which may be equivalent to altitudes of about 50,000 ft[1]. To pass this test, the cells must not leak, vent, disassemble, rupture, catch fire or have an Open Circuit Voltage (OCV) drop of more than 10% (unless fully discharged while being tested).

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[1] It is worth to note that the Normal Temperature and Pressure (NTP) is usually defined as 101.325 kPa and 20 degrees Celsius.

The IEC 60086-4 standard (Primary Batteries – Part 4: Safety of Lithium Batteries) [4] also has an altitude test. This test is similar to the UN test; cells are stored at room temperature for 6 hours at a total pressure of 11.6kPa or less. To pass this test the cells must not lose mass, leak, vent, have a short circuit, rupture, explode or catch fire. The IEC 62281 standard (Safety of primary and secondary lithium cells and batteries during transport) [5] also requires an altitude test with the same parameters except that the pass fail criterion does not include a loss of mass. The UL 1642 standard (Standard for Safety - Lithium Batteries) [6] requires the low pressure altitude simulation test (6 hours at 11.6 kPa). The pass fail criteria from this standard are no fire, no explosion, no venting or leaking. It is not clear why all the standards reviewed do not have a loss of mass except for the IEC 60086-4 [4].

The ANSI C18.2M, Part 2-2007 standard (American National Standard for Portable Rechargeable Cells and Batteries – Safety) [7] has the low pressure altitude simulation test as well (6 hours at 11.6 kPa). This test is required on fully charged and fully discharged samples, and on the first and fiftieth cycle. The standard requires no leakage, no fire, no explosion, no disassembly, no rupture, no venting, no mass loss and no OCV loss of more than 10%. Therefore, this standard covers new and used cells (up to 50 cycles similar to the UN) and it is probably meant for portable appliances that might experience low pressure during the cell lifecycle.

Other standards such as the IEEE 1625 [8] and 1725 [9] do not have an altitude test but they reference either section 38.3 of the UN Recommendations on the Transport of Dangerous Goods [3] or the IEC 62281 standards [5].

Table 2.1: Standards for low pressure testing.

Test	Pressure (kPa)	Time (hrs)	Temperature (°C)	Notes
UN TDG 38.3.4.1	11.6	6	15 - 25	OCV drop <10%
IEC 60086-4	11.6	6	Room temp	Batteries, No mass loss
IEC 62281	11.6	6	Room temp	Cells, No mass loss
UL 1642	11.6	6	N/A	
ANSI C18.2M Part 2	11.6	6	N/A	Fully charged and fully discharged

2.1.1 Ground transportation

During ground transportation, shipments are exposed to an atmospheric pressure, which depends on the altitude of the route taken and the weather conditions. Packages transported on the ground may be expected to experience altitudes as high as 3,658 m (12,000 ft)[2] when shipped over some mountain passes. The altitude of the highest roadway is reported to be 5,359 m (17,582 ft). This road is located in the mountains at Khardung La, Tibet. This road is at an atmospheric pressure of 51.5 kPa, which is about 50 kPa lower than at sea level.

[2]Which would result in an ambient pressure of around 64.9 kPa.

In regards to the weather, to date, the highest adjusted-to-sea level barometric pressure was 108.57 kPa [10] and the lowest was 87.0 kPa during the Typhoon “Tip” [11].

2.1.2 Marine transportation

Due to its very nature, Marine transportation is exposed only to weather related pressure changes, with the same historical maximum and minimum as in ground transportation (see above section 2.1.1). Hence, the maximum pressure differential that could possibly be experienced by a package would be about 21.5 kPa.

2.1.3 Air transportation

2.1.3.1. In flight

The Technical Instruction for the Safe Transport of Dangerous Goods by Air [12] highlights the pressure differential exposure of packaging generally filled at ground level at an average 100 kPa. Pressurized cargo compartments are typically kept at 75 kPa (cargo compartment pressure equivalent to 8,000 ft), which would results in a 25 kPa pressure differential with respect to the battery internal pressure. Non pressurized feeder aircrafts can be expected to climb up to 5,791 meters (about 19,000 ft) [13], which would result in an ambient pressure of around 48.5 kPa, which is about 51.5 kPa lower than at sea level.

A study carried out by Singh et al. (2010) [14] summarizes the data collected from 52 flights using cargo aircraft and 8 flights using passenger aircraft. This study showed that the pressure measured inside the cabin of passenger aircraft was not significantly different from the pressure measured inside the cargo hold. The highest pressure equivalent altitude was 17,454 ft (5,320 m) [14].

The feeder airplanes normally used, such as the Cessna Caravan, have a service ceiling of 25,000 ft but they are not made to routinely fly at those altitudes as they are meant to be used in trips of just a few hundred miles. These airplanes may climb to altitudes above 10,000 ft just to go above terrain or due to weather conditions.

UN regulation and other standards test cells up to altitudes of 50,000 ft, so in the event a cargo airplane experiences a cabin depressurization, the cells should withstand the pressure drop without a second event (cell failure).

2.1.3.2. At tarmac

The barometric conditions at the tarmac would depend on the weather with the most severe condition (described above in section 2.1.1), as well as the altitude of the airport. Eight of the ten highest airports are located in China with altitudes ranging from 3,448 m (11,312 ft) for Jiuzhai Huanglong Airport to 4,411 m (14,472 ft) for Daocheng Yading Airport. Under standard weather conditions, this would represent an atmospheric pressure as low as 58.4 kPa

2.2. Environmental humidity

Materials used to manufacture the outer shell of lithium batteries vary depending on the application. They can be plastic, aluminum or steel. Some plastics used are Polyether ether ketone (PEEK), polyethylene terephthalate (PET), Polypropylene (PP), Mylar and Acrylonitrile butadiene styrene (ABS). Some plastics are formulated with ceramic fillers. Steel may be coated with Nickel to prevent corrosion and promote welding ability (currently there is some development work on this topic). In cylindrical cells, when aluminum is used the battery needs to have reversed polarity (as compared to polarity in standard cells) or neutral to prevent corrosion of the can.

Prolonged exposure to condensation resulting from temperature fluctuations in humid environments, especially in salt environments, may corrode the lithium battery header[3] (Figure 2.1) and/or the monitoring circuit (Figure 2.2) creating the potential for external shorts.

Figure 2.1: Header of a cylindrical lithium battery © Rudolf Simon

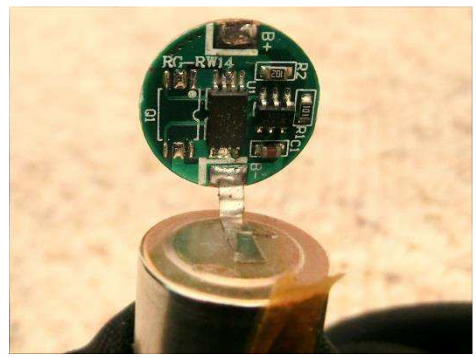

Figure 2.2: Monitoring electronics (over- and discharge protection)

The standards reviewed specify to store cells and batteries in cool, well ventilated and dry conditions away from rain, moisture, and humidity.

The IEEE 1625-2008 standard (IEEE Standard for Rechargeable Batteries for Multi-Cell Mobile Computing Devices) [8] has a conforming coating requirement in some applications to address the effects of microscopic droplets of water that can deposit on the insulation and weaken the electrical insulation between components of dissimilar voltages and on circuit boards.

Section 38.3 of the UN Recommendations on the Transport of Dangerous Goods does not have a high humidity test [3]. However this standard has an external short circuit test in section 38.3.4.5 (termed T.5). This test is performed starting with a cell temperature of 55°C after which a short circuit with an external resistance of less than 0.1 ohm is applied. The pass criteria are a temperature below 170°C, no disassembly, no rupture, and no fire up to six hours after the test. Cell testing standards such as UL 1642 [6], [15] and the IEC 62133 (Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for portable sealed secondary cells, and for batteries made from them, for use in portable applications) [15] also have short circuit tests. The

[3] The header is an engineered device, in cylindrical cells, that serves the purpose of providing a place to connect the cell to a device or application and include safety features such as current interruption, over-pressure protection, and a gasket to seal the can and isolates the anode and cathode potential.

IEEE 1725-2011 standard (IEEE Standard for Rechargeable Batteries for Cellular Telephones) [9] also has a short circuit test for battery packs.

The IEEE 1725-2011 standard [9] references Section 38.3 of the UN Recommendations on the Transport of Dangerous Goods [3], the UL 2054 standard [16], the UL 1642 standard [6], [15], the UL 60950-1 standard [17], the IEC 62133 standard [15] for the cell and the battery pack.

Some standards such as the ISO/DIS 12405-3 (Electrically Propelled Road Vehicles – Test Specifications for Lithium-Ion Traction Battery Packs and Systems – Part 3: Safety Performance Requirements) [18] require a dewing test on the battery packs and systems to simulate operating conditions. This standard references the dewing test procedure in the ISO 12405-1 standard (Electrically Propelled Road Vehicles -- Test Specification for Lithium-Ion Traction Battery Packs and Systems -- Part 1: High-Power Applications) [19] or the ISO 12405-2 standard (Electrically Propelled Road Vehicles - Test Specification For Lithium-Ion Traction Battery Packs and Systems - Part 2: High-Energy Applications) [20]. The UL 1642 standard [6] does not require a humidity test although it requires a short circuit test where the battery must not catch fire or explode to pass the test.

The UL 2580 standard (Standard for Safety – Batteries for Use in Electric Vehicles) [21] requires the metal pack enclosures to be corrosion resistant as determined in the CAN/CSA C22.2 No. 94.2 / Standard for Enclosures for Electrical Equipment, Environmental Considerations [22], and UL 50E [23]. It also prescribes insulating liners to be made out of non-moisture absorbent materials. Of course this standard requires a salt spray test to assess the ability of the energy storage assembly to withstand salt mist conditions and an immersion test (applicable to vehicles where the battery packs are underneath) as it is intended for vehicles. Similarly standards such as the SAE J2464 (Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System Safety and Abuse Testing) [24] and the SAE J2929 standard (Electric and Hybrid Vehicle Propulsion Battery System Safety Standard – Lithium-Based Rechargeable Cells) [25] have a salt water immersion test.

The SAE J2929 standard [25] does have a humidity/moisture exposure test to simulate the environment that a battery will experience in its life. The pass fail criteria for this standard is no venting outside of the enclosure, no enclosure rupture, no fire, no explosion and maintenance of high voltage to ground isolation. This standard refers this test to the IEC 60068-2-30 standard (Environmental testing - Part 2-30: Tests - Test Db: Damp heat, cyclic (12 h + 12 h cycle)) [26]. This IEC standard has the following scope:

"Determines the suitability of components, equipment or other articles for use, transportation and storage under conditions of high humidity - combined with cyclic temperature changes and, in general, producing condensation on the surface of the specimen. If the test is being used to verify the performance of a specimen whilst it is being transported or stored in packaging then the packaging will normally be fitted when the test conditions are being applied. For small, low mass specimens, it may be difficult to produce condensation on the surface of the specimen using this procedure; users should consider the use of an alternative procedure such as that given to IEC 60068-2-38."

The scope of the IEC 60068-2-38 standard (Environmental testing - Part 2-38: Tests - Test Z/AD: Composite temperature/humidity cyclic test) [27] is:

"IEC 60068-2-38:2009 provides a composite test procedure, primarily intended for component type specimens, to determine, in an accelerated manner, the resistance of specimens to the deteriorative effects of high temperature/humidity and cold conditions."

The ANSI C18.2M, Part 2-2007 standard (American National Standard for Portable Rechargeable Cells and Batteries – Safety) [7] require that in the case the electronics fail the battery must shut down. This is relevant to module and pack transportation.

The IEC 62281 standard (Safety of primary and secondary lithium cells and batteries during transport) [5] requires the packaging of cells and batteries in a way that avoids external short circuits but refers the packaging requirements to section 6.1 of the UN Model Regulations: 2011 [28].

The IEC 61427-1 standard (Secondary cells and batteries for renewable energy storage – General requirements and methods of test – Part 1: Photovoltaic off-grid application) [29] limit the storage humidity for lithium batteries to 90% with a maximum storage period of 12 months.

The IATA packing instructions 965 and 967 [30] have a requirement to have an inner package to fully enclose the cell or battery and a strong rigid outer package.

Not all standards directly address the hazard produced by high humidity and large temperature fluctuations while cells or batteries are being stored or shipped; also, compliance to standards other than the UN is not mandatory. This is an area that is currently not being covered. Air freight shipments are so short that the effects of corrosion may not be applicable.

IEC 62281 [5] states that "high temperature or high humidity may cause deterioration of the battery performance and/or surface corrosion". It specifies the packaging to prevent corrosion of the terminals, which could be interpreted to imply that the terminals must be in some way shielded.

The cardboard packing boxes do absorb some humidity but they can also release the humidity back to the goods. The use of descants inside the packages would help to deal with this issue. The fact that the IATA Packing Instructions require an inner packing that completely encloses the cells and an outer package, may be enough to isolate the cells from the high humidity outside. It is advisable to perform tests to confirm this, if not already done, and to quantify what it means to "fully enclose the cells or batteries".

Two areas of concern would be cells or batteries being transported by ship first and then by air, and batteries that have been stored for longer periods before being shipped. The regulations concerning lithium battery sea transport in International Maritime Dangerous Goods (IMDG), published by the International Maritime Organization (IMO), do not have requirements more stringent that section 38.3 of the UN [3] with respect to humidity.

Table 2.2: Standards for humidity and short circuiting safety.

Standard	Description
UN TDG 38.3.4.5	External short circuit test
UL 1642	External short circuit test
UL 2580	Corrosion resistance test
IEC 60068-2-38	General humidity test
IEC 61427-1	Relative humidity storage limit
IEC 62133	External short circuit test

IEC 62281	External short circuit avoidance
IEEE 1725	External short circuit test
ISO/DIS 12405-3	Dewing test
SAE J2929	Humidity / moisture exposure test
IATA 965 & 967	Inner packaging requirement

2.2.1 Ground transportation

The periods of time that the cargo spends on trains, truck and storage frequently have large daily temperature and humidity cycles. However, the rapid temperature changes that occur during ground transportation seem to have little effect on batteries due to the insulation effect of the packaging [31]. In one study the relative humidity inside a box changed from 60.15% to 60.41% while the external relative humidity changed from 58% to 87% during a 15-hours period when a container was stored outside [31].

2.2.2 Marine transportation

High levels of humidity are usually found inside sea vessels and shipping containers. Also, intercontinental shipments across the equator incur climatic changes that can cause changes in humidity, moisture content and dew point, causing condensation. Furthermore, transporting goods from a hot and humid environment, such as tropical regions, and delivering them in cold regions, or just transiting through these cold regions, will expose the goods to a phenomenon known to the industry as “cargo sweat” or “container rain” [32]. In a study on the transportation of containers from Nagoya in Japan to Portland in USA [33], it was found that the most extreme conditions of relative humidity are seen during periods of large daily temperature changes. For example, the highest relative humidity was recorded in Portland, after the container temperature dropped from 49°C to 20°C and the relative humidity increased from 32% to 96% over a 16 hour period.

The moisture content of pallets used to transport goods may seem inconsequential; however, they could be a significant a secondary source of humidity. The pallet industry is a just-in-time market sector and pallets arriving at the loading docks are likely to be green and laden with moisture content ranging from 35 to 60%.

It was observed that corrugated boxes seem to absorb moisture fast enough to temper humidity during slow changes in temperature while at sea, hence reducing the cargo sweat, but potentially transferring the humidity to the goods.

2.2.3 Air transportation

2.2.3.1. In flight

On most flights condensation occurs on the airplane structure because of its cold temperature, which is below the dew point of the cabin. The condensation usually manifests itself as frost [34]. In closed or very tight containers, condensation could occur if there is a rapid change of temperature, but would only result from the humidity of the air inside the container. In this case, the small volume of the container makes the probability of significant condensation on items inside the container low.

2.2.3.2. At tarmac

The cargo is exposed to the humidity and temperature conditions in the hub warehouse. Then it is exposed to the local weather temperature and humidity (possibly to rain) as it waits to be loaded into the airplane. The worst case scenario would be when containers are exposed to rain and are not water proof. In this case the contents of the container may get exposed to high humidity or water. If a cell or battery terminals are flooded with water the battery will most likely discharge causing water electrolysis and hydrogen generation.

2.3. Environmental temperature

Extreme temperatures can cause damage to cell components, leading to a loss in cell performance or cell failure. Extreme temperature during battery discharge can lead to a runaway thermal reaction and fire. The storage temperature should never exceed manufacturers' guidelines. Industry standards specify storage of batteries in cool, well ventilated and dry conditions out of direct sunlight.

Shipping containers can pose a risk of extreme high temperatures as stated in IEC 61427 (Secondary cells and batteries for renewable energy storage – General requirements and methods of test) [29]: "The temperature of a battery stored in a shipping container in direct sunlight, can rise to +60°C or more in daytime. Choice of a shaded location or cooling should avoid this risk."

High temperatures affect both the integrity and performance of batteries and a number of the certification standards require High Temperature Endurance and Temperature Cycling tests to determine the effects of high temperatures on cells.

High Temperature Endurance / Heating / Thermal Abuse

High temperature endurance is required by some standards to determine thermal stability (IEC 62660 [35], UL 1642 [6], ANSI C18.2M pt2 [7]). This testing consists of a hot-box soak and dwell. A typical method starts at ambient temperature (20-23°C), ramping to 130°C (170°C for lithium metal) with a defined rate of temperature increase (5 K/min) and holding at temperature for 10 to 30 minutes depending on the standard. With most standards, the battery is considered to have passed if it did not explode, leak, disassemble, rupture or catch fire, with the exception of IEC 62660 [35], which requires documenting any noticeable change to the cells.

Temperature Cycling / Thermal Shock

Thermal cycling is prescribed by some standards (IEC 62660 [35], UL 1642 [6], ANSI C18.2M Part 2 [7], IEEE-1625 [8], UN TDG § 38.3 [3], IEC 62281 [5]) to determine the effects of rapid, extreme temperature fluctuations on the integrity of cells and batteries, their seals, and electrical connections. Damage occurs due to expansion and contraction of battery components. The UL 1642 [6][6] test procedure consists of placing the cells or batteries in a thermal chamber, ramping to 70°C within 30 minutes, holding for 4 hours, cooling back to ambient within 30 minutes, holding for 2 hours, cooling to -40°C within 30 minutes and holding for 4 hours. This cycle is repeated 10 times. After completion of cycling, the cells are held at ambient temperature and observed for 24 hours. The samples must not vent, leak, explode or catch fire.

The ANSI C18.2M Part 2 [7] thermal cycling test procedure is similar to that of UL 1642 [6], but stipulates a maximum temperature of 75°C and dwell times to 6 hours at the maximum and minimum temperatures. After the test there should be no rupture, leakage, fire, explosion, disassembly, venting, mass loss and the Open Circuit Voltage (OCV) should not degrade by more than 10%.

The IEC 62660 [35] thermal cycling test procedure stipulates a minimum temperature of -40°C, a maximum temperature of 85°C, and a maximum of 30 minutes to reach the temperature extremes. The UN TDG § 38.3 [3] test procedure is based on IEC 62660[35], but has a lower maximum temperature of 72°C. Both tests require 10 cycles. After a resting period of 24 hours there should not be leakage, venting, disassembly, rupture or fire and the OCV should not degrade by more than 10%.

Table 2.3: Standards for temperature testing.

Standard	Temp Range (°C)	Ramp Time (min)	Dwell Time (hrs)	Number of Cycles
UN TDG 38.3.4.5	-40 to 72	30	6	10
IEC 62660	-40 to 85	30	6	10
UL 1642	-40 to 70	30	4	10
ANSI C18.2M Part 2	-40 to 75	30	6	10

2.3.1 Ground transportation

Packages shipped through ground transportation can be exposed to extreme temperature. Weather record temperatures range from 54°C (recorded at the Death Valley, USA, and Mitribah in Kuwait) to -57°C at the Rogers Pass in Montana, USA.

Adding to record high temperature, cargo left under the sun can experience 15°C higher temperature than ambient.

2.3.2 Marine transportation

Extreme temperatures can occur inside sea vessels and shipping containers due solar radiative heating and the humid environment. When crossing the equator, temperatures inside shipping containers can rapidly rise to more than 60°C during the day. In a study on the transportation of containers from Nagoya, Japan to Memphis, USA [33] the highest temperature recorded was in July at 57°C; the lowest temperature recorded was in January at -29°C, a temperature variance of 86°C. Interior temperatures of different containers on the same ship vary depending on the location of the container. Direct sunlight causes the upper part of the container to be more than 15°C warmer than the ambient air. Containers stored below deck will be cooler during hot, sunny voyages. Even the location of boxes within the container is important as the bottom row of boxes in a container can be up to 20°C cooler than the top row of boxes.

2.3.3 Air transportation

2.3.3.1. In flight

The environmental conditions in the aircraft cargo area are affected by the weather at the airport and along the flight path of the aircraft at altitude which can change greatly. In the lower atmosphere, <11 km, the temperature decreases by approximately 6.4 °C / km in altitude. Between an altitude of 11 and 20 km the temperature is relatively constant. At a typical cruising altitude of 35,000 – 43,000 ft the temperature is typically in the range of -50 to -60°C, but varies depending on the ground temperature. Although some cargo hold areas are temperature controlled, cargo can experience a wide range of temperatures during the air transportation cycle depending on the heating/cooling and insulation of the cargo compartment. A study carried out by Singh et al. in 2010 summarizes the data collected from 52 flights using cargo aircraft and 8 flights using passenger aircraft. This study showed the temperature to range between 15.7-23.9°C [14].

Due to the high cost of fuel and operation time (aircraft cost per hour), cargo aircrafts are conditioned during flight operations but not prior to loading and departure. Therefore, the packages inside the aircraft cargo area may experience temperature extremes and rate of changes dependent on the airport warehouse conditions, airport weather, flight duration and container system or Unit Load Device (ULD) containers being used which offer some insulation. For example, during the winter, it may take a long time of flight to condition the aircraft to a comfortable temperature. The same could be true for very warm conditions during the summer. Furthermore, feeder aircrafts may not have advanced temperature control. Similarly, cells and batteries within a package may experience temperature changes depending on the insulating effect of the package material (internal and/or external), cushioning material, the size of the package and location within the aircraft.

2.3.3.2. At tarmac

The structural integrity of most tarmacs used on aircraft aprons and taxiways begins to degrade when exposed to temperatures of 32°C and above [36]. Elevated temperatures also increase the safety hazards of ground crew involved in fueling aircraft as the flashpoint of jet fuel is 38°C. At London's Stansted Airport, temperatures peaked at 37.3°C in the summer of 2003 and the temperature on the tarmac reached 80°C from solar heating. As climate warms in the medium to longer term, rising temperatures will lead to an increased fire risk on and round the airfield [37].

A pallet of unprotected product on an airport tarmac with an ambient temperature of 21°C can quickly reach temperatures above 55°C due to solar heating effects. Tarmac and aircraft off-loading and transporting to terminal can take 2-10h, exposing cargo to extreme temperatures for extended periods.

According to DuPont, shipments could reach unsafe temperatures inside a pallet wrapping or ULD due to a greenhouse effect of solar gain, a phenomenon that can be further exacerbated by heat radiating off the tarmac, "pavement radiation", and the "mirror" effect nearby glass and metal clad buildings. Packages can experience very hot conditions while on the tarmac followed by relatively cold conditions while on flight or if landing in the northern hemisphere during winter.

2.4. Environmental air quality

Air quality includes pollution; exhaust gases from vehicles or aircrafts (CO_2, CO, VOC, NO_x, SO_x, etc.), particulate matter from diesel engine exhaust as well as dust. Because lithium batteries are sealed, and completely enclosed and packaged with double packaging in accordance to the IATA packing instructions [30], they are not susceptible to pollution or dust deposition.

3. MECHANICAL STRESS EXPOSURE

Mechanical stresses including shock, drop, vibration, impact, crush puncture and abrasion, occur during handling of cargo. Of these stresses, shock and vibration are the easiest to quantify and test by standardized means. The energy in vibration and shock systems is usually expressed as root mean square acceleration (G_{rms}). This value can be calculated by squaring the magnitude of the shock or vibration signal at every time step, calculating the average of these values and taking the square root of the average value. This allows the average mechanical stress from shock or vibration to be determined for a given bandwidth [38].

Shocks and vibrations were measured in most studies selected for this review. It is important to know that these mechanical parameters were measured using tri-axial accelerometers; hence, shocks are often reported directly in terms of acceleration. Other studies report shocks by calculating a free-fall height based on the period of time between zero acceleration and peak acceleration. The free-fall height is a well-established measurement in various standards. On the other hand, the direct acceleration data depends significantly on the apparatus and the configuration used for the measurements. The following sections, 3.1 and 3.2, describe how current codes and standards address mechanical stress exposure. Sections 3.3 through 3.5 are a summary of the studies reviewed for the different modes of transportation.

3.1. Lithium batteries required standards testing

3.1.1 Shock

The shock test is performed to mimic rough handling throughout the transportation cycle (IEC 62660 [35], UL 1642 [6], IEEE-1625-2008 [8], UN TDG § 38.3 [3], IEC 62281:2012 [5]). Some protocols use fresh cells, others (IEC 62281:2012 [5]) use cells that have already undergone vibration testing. In some standards cells are subjected to shocks on each axis, in both directions to an acceleration of 150 g for 6 ms. The UL 1642 [6] standard uses 3 ms and a total of six shocks on each axis. This is a total of 18 shocks. Cells are then observed for post-tests effects. The UN TDG § 38.3 [3] pass criteria includes no leakage, no venting, no disassembly, no rupture, no fire, no explosion and the OCV should not degrade by more than 10%. The IEC 62281 [5] pass criteria require no leakage, no venting, no short circuit, no rupture, no fire and no explosion during the test.

3.1.2 Package drop

The package drop test is prescribed by some standards to confirm package performance during rough handling (IEC 62281:2012 [5], IEEE 1625-2008 [8], UL 2054 [16], IATA Dangerous Goods Regulations 55th Edition [30]. In the IEC 62281 [5] drop test, packages are dropped from a height of 1.2 m to a hard flat surface (concrete) in such a manner that they land on a corner of the package. Shipping packages are tested, not palletized loads. The pass criteria are no shifting, no distortion, no leakage, no venting, no short circuit, no excessive temperature rise, no rupture, no fire and no explosion during the test. The IATA Packing Instructions 965, 966, 968 and 969 [30] have the 1.2 m drop in any orientation requiring no damage to the cells or batteries, no shifting that can allow battery to battery contact and no release of contents.

3.1.3 Free fall

The free fall test is prescribed by a few standards [ANSI C18.2M Part 2 [7]; IEC 60086-4] to capture when batteries are inadvertently dropped. In the ANSI C18.2M Part 2 [7], free fall test consists of dropping the batteries (on each orientation for a total of three drops, except for cylindrical batteries which are dropped six times) from a one meter height on a cement surface. After one hour the sample passes if there is no leakage, no rupture, no fire, no explosion, no disassembly and the integrity of the protective devices are maintained. The IEC 60086-4 [4] standard has the same test but has six drops (one for each face on a prismatic cell). This standard requires no fire, no explosion and no venting after one hour of observation.

3.1.4 Vibration

Some standards have a vibration test (IEC 62660-2 [35], UL 1642 [6], UN TDG §38 [3], IEEE 1625-2008 [8], IEC 62281 [5]) to simulate the shipping conditions. The IEC 62281 [5] vibration test requires the specimens to be exposed to harmonic motion (sine wave) from 7 Hz to 200 Hz and back to 7 Hz in 15 minutes. The vibration is repeated 12 times for each perpendicular axis. Each axis is performed discretely. There is no provision or exclusion, for performing this test with a harmonic motion that is blended on 3 linear axes. Also, there is no suggestion to include rotational shear for a total of 6 axes. NRC's interpretation of this standard is that the test is to be performed on one linear (orthogonal) axis at a time. The pass criteria from this standard are no leakage, no venting, no short circuit, no rupture, and no fire or explosion during the test.

The UN TDG §38 [3] pass criteria are no leakage, no venting, no disassembly, no rupture and no fire or explosion during and after the test. Also, the standard requires the OCV not to drop by more than 10% right after the test. The UL 1642 [6] standard prescribes a different frequency range between 10 to 55 Hz at an increase rate of 1 Hz/min for 100 min per axis on 3 orthogonal axes. The pass criteria are no venting, no leakage and no fire or explosion. Other standards such as the IEC 62660-2 [35] have different vibration requirements as they are meant for electric road vehicle applications and thus the vibration test is meant to address the application and not the transportation of the cells or batteries.

3.1.5 Impact and crush

The standards (UL 1642 [6], UL 2580 [21], ANSI C18.2M Part 2 [7], UN TDG §38 [3]) have other mechanical tests which would only be applicable if the protection provided by the packaging fails. These additional mechanical tests include the crush and impact tests. The crush test from UL 1642 [6] consists of placing the battery in between two flat plates and applying a 13 KN force. No fire or explosion should occur. The impact test, from the UL 1642 standard [6], consists of placing the cell on a flat surface and then laying a 15.8 mm diameter bar on top of the cell at the center and then dropping a 9.1 kg weight onto the sample from a height of 61 cm.

The UN TDG §38 [3] has these tests even though damaged packages containing cells and batteries are not to be transported by air [39]. The pass criteria from the UN TDG §38 [3] is no disassembly, no fire and an external temperature at or below 170°C during the test and within six hours after the test. The ANSI C18.2M Part 2 [7] has a crush test to mimic trash compacting and thus not relevant for transportation, as well as a crush test to simulate reasonable compression on the battery which consists of placing the battery between two plates and applying a weight of 114 kg. The pass criteria are no fire, explosion or disassembly.

3.2. Packaging requirements

The Air Line Pilots Association (ALPA), which represents pilots from the USA and Canada, has been working to improve the shipment of lithium batteries through the International Civil Aviation Organization's (ICAO) Dangerous Goods Panel for more than 10 years [40]. ALPA requested that lithium batteries be shipped by cargo aircraft only (as declared dangerous goods) because of safety reasons [41]. In January 2015, IATA/ICAO banned lithium metal battery shipments on passenger aircrafts [42] and as of April 1, 2016, the ICAO banned lithium ion batteries from being shipped in passenger airplanes as well [43].

For cargo shipments the regulations restrict the quantity of batteries in a single shipment based on the watt-hour ratings of the batteries. In doing so, they limit the amount of lithium contained in the shipment because watt-hours are the equivalent of voltage multiplied by ampere-hours and one ampere-hour requires about 0.3 grams of lithium. Lithium ion cells with Watt-hour ratings in excess of 20 Wh are assigned and shipped as dangerous goods [12]. Assuming a voltage of 3.6 V in a cell, the equivalent lithium content of a 20 Wh cell is about 1.6 g. Also, batteries with a multi-cell Watt-hour rating greater than 100 Wh need to be shipped as dangerous goods. A second parameter that will also limit the level of reactivity of the battery shipment is the state of charge, which is being restricted to 30% as lithium batteries are more stable at lower SoC [12].

Lithium battery shipments must pass section 38.3 of the UN Manual of Tests and Criteria [3]. IATA is the publisher of the Dangerous Goods Regulations (DGR) [30], which is recognized by the airlines. Some of the instructions contained in this DGR are:

- Classifications of dangerous goods,
  Packing instructions for dangerous goods,
- Marking and labelling, and
- Documentation.

The IATA Packing Instructions (PI) 965 through 970 cover lithium ion cells and batteries (PI 965), lithium ion cells and batteries packed with equipment (PI 966), lithium ion cells and batteries contained in equipment (PI 967), lithium metal cells and batteries (PI 968), lithium metal cells and batteries packed with equipment (PI 969) and lithium metal cells and batteries contained in equipment (PI 970).

Anyone shipping lithium-ion batteries in bulk must meet transportation regulations, and this applies to domestic and international shipments by land, sea and air. Sea transport regulations are prescribed by the International Maritime Dangerous Goods Code (IMDG). Land transport regulations are country specific for now [4].

Laboratory evaluations are usually the first step in evaluating the performance of packaging used for shipping products. Once the laboratory tests are successful, shipping trials are carried out with various carriers. ASTM D4169, Standard Practice for Performance Testing of Shipping Containers and Systems [44], and ASTM D7386, Standard Practice for Performance Testing of Packages for Single Parcel Delivery Systems [45], guide the manufacture on the tests to be carried out to evaluate the packaging performance in the distribution cycle and as a single shipment respectively.

ASTM D7386-16 [45] provides the basis for evaluating packages under 68 kg in single shipment. The evaluation includes:

- water resistance by spray method (ASTM D951),
- bridge impact testing (ASTM D5265),
- drop of loaded container (ASTM D5487),
- rough handling (ASTM D6179),
- concentrated impact (ASTM D6344), and
- high altitude (ASTM D6653).

ASTM D4169 -16 [44] evaluate packages integrity when dealing with the whole distribution cycle. The evaluation includes:

- determination of the compression resistance (ASTM D642),
- impact testing for shipping container (ASTM D880, D6344),
- water resistance by spray method (ASTM D951),
- vibration testing of shipping containers (ASTM D999),
- horizontal Impact test for shipping containers (ASTM D4003, D5277),
- random vibration testing of shipping containers (ASTM D4728),
- bridge impact testing (ASTM D5265),
- drop test of loaded container (ASTM D5276, D5487), and
- mechanical and rough handling (ASTM D6055, D6179).

ISTA has also defined 7 series of test procedures to challenge the product and package combination. One series includes ISTA member defined procedures for testing packages under and over 68 kg, as well as testing through the distribution system.

It needs to be noted that MIL-STD-810G [46], Environmental Engineering Considerations and Laboratory Tests, defining the environmental test methods includes a more complete set of test covering a wider range of potential hazards:

- Low Pressure (Altitude)
- High Temperature
- Low Temperature
- Temperature Shock
- Contamination by Fluids
- Solar Radiation (Sunshine)
- Rain
- Humidity
- Fungus
- Salt Fog
- Sand and Dust
- Explosive Atmosphere
- Immersion

- Acceleration
- Vibration
- Acoustic Noise
- Shock
- Pyroshock
- Acidic Atmosphere
- Gunfire Vibration
- Temperature, Humidity, Vibration, and Altitude
- Icing/Freezing Rain
- Ballistic Shock
- Vibro-Acoustic/Temperature

The ASTM D4169 is commonly used to assess the adequacy of high performance packaging systems for the medical, pharmaceutical and other industries [44].

3.2.1 Packaging requirements addressing puncture, abrasion

Both the IATA packing instructions (965, 966, 968, 969 and 970) [30] as well as the IEC 62281 [5] standard specify the package to be strong for the expected shocks and loadings. NRC is not aware of a specific test for puncture or abrasion of battery packaging.

3.2.2 Packaging requirements addressing compression

The IEC 62281 [5] requires the boxes not to be stacked exceeding the height recommended by the manufacturer. This standard also specifies that the packaging must prevent crushing of the cells or batteries during rough handling. The IATA packing instructions (965, 966, 968 and 969) specify to place the inner package inside a strong outer package to protect the batteries from compression forces. The IATA Packing Specifications and Performance Tests of the Dangerous Goods Regulations [30] include a stacking test designed to ensure that packages can withstand the compression of stacking boxes on top of each other. The equivalent force is the weight of loaded boxes seating on top of the test box for a total height of 3 m.

3.2.3 Packaging requirements addressing shock

Shock may be simulated with the 1.2 m Package Drop test described in section 3.1.2.

3.2.4 Packaging requirement addressing vibrations and environmental conditions

Section 5.0.2.4.1 of the IATA packing instructions [30] specify: "packages must be constructed and closed as to prevent any loss of contents when prepared for transport which might be caused under normal conditions of transport, by vibration or by changes in temperature, humidity or pressure (resulting from altitude for example)". IATA Packing Instructions 965 require an inner packing that completely encloses the cells and an additional outer package enclosure which should isolate packaged cells from outside humidity. NRC is not aware of specific tests for vibration or humidity for battery packaging.

3.3. Ground transportation

Review of studies looking at package handling during ground transportation focussed on shock, vibration and damages to packages (puncture, abrasion, compression). In general, the reviewed literature suggests that vibration levels are different among different modes of transportation, and are generally higher in truck and rail transport than ship transport.

The transportation environment specific to truck vibration levels in Central Europe showed lower levels as compared to those measured in North America [31]. The highest recorded shock events occurred when packages were being handled during the transfer between different storage modes or moving to storage. The ten most severe shocks while shipping packages from Eastern Europe to the equator and then to South Africa ranged from 4.48 g (on a flat back orientation while being handled at port) to 13.11 g (on a flat bottom orientation while being handled at commissioning)[47]. The most severe physical events happened when the unit was handled at the ports or during transfer between storage and loading on trucks.

In a recent study by Singh et al (2015) measurements showed that the existing power density spectrum used for laboratory validation of air and truck transportation (ASTM 4169 [44]) were not representative of the actual measurements. The authors proposed a new spectrum that raises the power density in the range of 20 to 60 Hz [48]. See section 6 for more details.

3.4. Marine transportation

The vibration and shock levels were generally very low when the package system was being transported by ship. Shocks while cargo is inside containers may not be excessive as containers are only made to withstand 2 g_{rms} and thus it is not likely that this value is exceeded. Also, as mentioned in the previously, the reviewed literature suggests that vibration levels are generally higher in truck and rail transport than ship transport.

3.5. Air transportation

Shipping by air involves different modes of transportation. For example, a truck will pick up the product, moves the product to the airport, and the freight is processed and loaded onto an airplane. At the destination airport, the freight is removed from the airplane, processed, loaded onto a truck, and moved to final delivery.

In the study from 1991 to September 15 2016 [49], the FAA recorded 129 air incidents involving lithium batteries leading to smoke, extreme heat, fire or explosion. The underlying cause of most incidents was inappropriate packaging or handling, occurring at airports or cargo hubs. The following variables may impact the outcome, should thermal runaway occur:

- The total number, size/type, and chemistry of lithium batteries on board the aircraft, including state of charge if know;
- The batteries' proximity to one another; and
- The location of the batteries in association with other dangerous cargo

3.5.1 In flight

It is generally accepted that the level of shock and vibration that freight is exposed to on board airplanes is lower than at any other phase during the transportation cycle [50], Figure 6.1 shows the typical power density spectrum during the air transportation cycle. Vibrations are typically reported using power density spectra in the range of 1 to 250 Hz [48]. As mentioned in the ground transportation section, Singh et al (2015) [48] showed that the existing power density spectrum used for laboratory validation of air and truck transportation (ASTM 4169 [44]) were not representative of the actual measurements and proposed a new spectrum that raises the power density in the range of 20 to 60 Hz.

3.5.2 At tarmac

In some of the studies done for air transportation it was difficult to correlate shocks with the exact location (e.g., at the sorting facilities or the tarmac) in two of the studies measuring the transportation environment at airport tarmacs in San Francisco, CA, USA [51] and in Vatry, France [52]. Earlier studies [50] and [53] indicated that the highest shocks were observed on tarmacs. It was interesting to note that packages experienced more stress on the tarmac at John F. Kennedy Airport than at the other airport in the study. The results were attributed to uneven surfaces and careless driving. The maximum drop height recorded was 2.15 m in a domestic delivery within the USA. However, 99% of the falls occurred from a 1.26 m height.

4. HUMAN FACTORS

Human beings are imperfect machines and despite the most stringent engineering controls and procedures, improper handling of cargo can lead to serious injury to persons or property. Incidents may be the result of:

- human error or mistakes,
- lack of awareness of safety procedures,
- non-compliance to safety procedures,
- insufficient training, and
- poor communication between workers.

Employees involved in cargo/baggage handling tasks at airports are subject to high levels of stress due to the fast paced time sensitive nature of cargo/baggage handling. The large number of load handling operations and the weight of the baggage items lead to strain upon the musculoskeletal system, particularly the back. In addition, ramp agents must load and unload the low baggage compartments of narrow-body aircraft in a kneeling posture. This mental and physical fatigue combined with the time sensitive nature of cargo delivery can easily lead to mishandling of cargo packages and shortcuts taken in handling procedure; leading to excessive shock on cargo or improper packing.

Knowledge and compliance with correct procedures is paramount to insuring safe operations. Even if personnel must be instructed in the correct procedures it is ultimately their decision to abide by them or not. Proper training can inform personnel of procedures and the underlying reasons for the procedures to ensure compliance.

There are numerous examples of human error in cargo handling at airports that led to catastrophic loss of property and life. One example of human error leading to lithium batteries catching fire is a fire at the Northwest Airlines cargo facility at Los Angeles Airport (LAX). Two pallets of batteries were destroyed. One pallet contained 100,000 primary lithium cells (Sanyo CR2 Li/MnO_2); the other 20,000 of these cells and rechargeable cells as well. The pallets were damaged by forklift operators as they moved them around an outdoor cargo area, without the care required for such cargo. This indicates lack of knowledge (possibly due to lack of training) or compliance with correct handling procedures. This led to a fire, potentially caused by destruction of the packaging integrity allowing the cells to move into contact with one another. Ignition could have started by any of the following mechanisms: crushing of cells, short circuiting of cells, charging or forced charging [54].

More recently, numerous airlines have updated their boarding procedures to include instructions from flight attendant for all Samsung note 7 phones to be turned off prior to takeoff. Despite this measure, a number of fires involving the devices have been reported. The SP 137 of Transport Canada requires defective batteries to be packed in accordance to packing Instructions P908 or LP904 of the UN Recommendations and forbids their transportation by aircraft.

Often it requires a number of failures on the part of personnel to lead to an incident. On 1 April 2014, an Airbus A300B4-622R Cargo Aircraft arrived at Abu Dhabi International Airport. Ten of the thirty cargo containers and pallets were due to be unloaded at Abu Dhabi. While unloading the final pallet bound for Abu Dhabi, the Aircraft tipped onto its tail. The loadmaster left the Aircraft before the unloading was complete and a shift change of the ramp team occurred during the unloading. The investigation identifies the following contributing human factors to the Incident: [55]

- Poor communication: Inadequate briefing provided by the loadmaster before the unloading process commenced and before leaving. No communication between the shift teams.
- Lack of procedural awareness: The loadmaster was the only one with knowledge of loading and unloading procedures, but was absent during the final unloading.
- Insufficient training: The loadmaster had not been provided the DHL Operations Manual.

Human error by cargo aircraft loading crews has also resulted in loss of life. On April 29, 2013, a Boeing 747-400 BCF, operated by National Air Cargo, Inc. crashed shortly after takeoff from Bagram Air Base, Afghanistan. All seven crewmembers were killed and the airplane was destroyed. Human factors related to the accident were a result of lack of Federal Aviation Authority (FAA) training/certification for cargo handling personnel [56].

The International Coordinating Council of Aerospace Industries Associations (ICCAIA), airplane manufacturers Boeing and Airbus, the International Civil Aviation Organization (ICAO), and the FAA have worked together to establish recommendations for transportation of lithium batteries. The implementation of the Safety Management System (SMS) is listed as critical to the safe handling of lithium batteries. The SMS includes the Safety Risk Assessment (SRA), which helps transporters assess the risk of carrying lithium batteries [39]. Training of the personnel who handle the batteries must include the risks posed by lithium batteries and information on the dangers of lithium batteries, proper labelling, proper loading, and rejection criteria for damaged items. Knowledge of the dangers could help to increase compliance of safe handling procedures outlined in the SMS [57].

Appropriate, standardized procedures for the safe handling and transporting lithium batteries are required to avoid incidents. It will require a collaborative effort by all parties including airlines, airplane manufacturers, regulatory agencies, battery producers, package manufacturers and airports, to formulate these protocols and insure their compliance. Procedural oversight and engineering controls can be built in to minimize the potential for serious incident, but ultimately, it is down to the individual if they choose to follow the protocol or not and incidents will occur as a result.

5. BATTERY SOC WHILE IN THE TRANSPORTATION CYCLE

The State of Charge (SoC) of a battery is an estimate of the percentage of the total energy that remains available and can be discharged. Estimating the SoC is complicated because there is no standard SoC measurement protocol, and there are many variables that affect the measurement (e.g. temperature and measurement technique) [58].

Lithium ion batteries are more stable at lower SoC. However, they should be stored at around a 40 percent SoC to minimize storage-related capacity loss while keeping the battery operational and allowing for some self-discharge. The voltage of Li-ion battery should not drop below 2V per cell [59], which is considered an over-discharge condition. In this over discharged condition, recharging the cells may render them unstable, causing excessive heat or showing other anomalies. Li-ion batteries that have been under discharge stress may function normally but are more sensitive to mechanical stresses.

When it comes to fire safety, the available heat during thermal runaway includes the electrical energy (SoC) plus the heat of combustion of the flammable materials. For some battery chemistries the heat of combustion from the electrolyte is approximately half of the heat of combustion from gasoline. The lower the SoC, the lower the energy that is available during a thermal event.

Shocks or manufacturing defects can lead to internal short circuits which generate heat inside the battery. At a low SoC, there less energy available for heat generation in the case of an internal short circuit and the battery is more stable. This lowers the probability of a thermal runaway and for this reason lithium batteries are now required to be shipped with a SoC of 30% or below. This SoC requirement is difficult to enforce since SoC cannot practically be measured in the field; therefore, this requirement is based on an honor system where shippers are required to declare compliance. Third party factory inspections to verify the use of a reasonable Quality Assurance Program by battery shippers including a protocol to determine SoC would be advisable [58].

6. ASSESSMENT OF THE SHIPPING CONDITIONS

6.1. Evaluation tools and methods

6.1.1 Applicable standards

Thorough literature search didn't yield any standard that would guide the assessment of the environmental conditions experienced by parcels during shipping. ASTM D4169 [44] only refers to a series of laboratory testing to simulate the parcel distribution cycle, covering manual handling, compression testing (vehicle stacking), loose-load vibration (ground transportation), low pressure (high altitude), random vibration (ground and air transportation), and concentrated impact.

6.1.2 Data loggers

In order to evaluate the environmental conditions during actual shipping of parcels using courier, a certain number of sensors and data loggers needs to be installed within the parcels to be shipped. The electronic and energy source needs to comply with the RTCA-DO160G - section 21 [60] to ensure there is no electro-magnetic interference with the aircraft.

Published studies reporting environmental conditions tends to use compact measuring equipment that combines several sensors, data logging and power source in one single unit. The following list is only an overview of all the available electronic systems used to assess the environmental conditions:

- EDR-3C from Instrument Sensor Technology: measures shock, vibration and temperature, with option to measure humidity, pressure, strain, and loads;

- Saver 3X90 from Lansmont Corporation: measures shock, vibration, temperature and humidity;

- PRTemp110 from MadgeTech: measures pressure and temperature;

- GP1 from SENSR: measures shock and vibrations.

It is to be noted that manufacturers of sensitive equipment are commonly using one-time use indicators that are triggered when environmental conditions exceed the limit of the indicators.

6.1.3 Experimental plan

The following paragraphs describes the various parameters taken into account in published reports studying environmental conditions of package shipping.

6.1.3.1. Shipping route

Transportation routes were reported in most studies, though limited to departure and arrival locations. Only a few studies provided more details about the transfer hubs being used. Overall, freight transportation environmental condition studies have been carried out across 9 states within the USA and in nine other countries. Some studies reported difficulties in correlating measured data with the location where the events were being measured. The data measured was time-based and test packages experienced delays at various steps of the transportation cycle. Carrier tracking systems offered useful information to correlate the location of the event with the time-based data.

While time-based events can efficiently distinguish amongst ground and air transportation, the exact location of package transfer can only be obtained from the courier company and their parcel tracking systems. Newer environmental data loggers have an optional built-in global positioning system to provide a secondary mean of auditing.

It is interesting to note that two of the studies were solely focused on measuring the transportation environment at airport tarmacs in San Francisco, CA, USA [51] and in Vatry, France [52]. Earlier studies [50], [53] had already indicated that the highest shocks were observed on tarmacs. It was interesting to note that packages experienced more stress on the tarmac at John F. Kennedy Airport (JFK) than at the Stockholm Arlanda Airport (ARN). The acceleration levels were between 0.08 and 0.18 $m.s^{-2}$ at ARN, while they were between 0.26 to 0.51 $m.s^{-2}$ at JFK. The results were attributed to uneven surfaces and careless driving. A more detailed review of each airport in regard to the surface evenness of their tarmac, personnel training, number of claims related to ergonomic injuries (repeated heavy lifting) could be carried out to identify airports more prone to induce higher shocks and vibration to packages.

It is also important to note that most of the studies lack repeatability in the measurements. Most of the studies report results of only one trip. Only one study, carried out by Singh et al in 2009 [14], had results from 52 cargo flights and 8 passenger flights. Since a large number of external parameters come into play and affect the measurements, repetition of experiments could only consolidate mean values of environmental conditions experienced by parcel, but wouldn't enable the establishment of absolute extreme values.

Table 6.1: Routes being used for freight environmental assessment

Departure	Via	Arrival	Reference
CA, USA	NA	Cape Canaveral, FL, USA	[61]
East Lansing, MI, USA	NA	San Francisco, CA, USA	[62]
East Lansing, MI, USA	NA	Orlando, FL, USA	[62]
East Lansing, MI, USA	NA	San Luis Obispo, CA, USA	[14], [38], [47], [63]
East Lansing, MI, USA	NA	Rochester, NY, USA	[47]
East Lansing, MI, USA	NA	Twin Falls, ID, USA	[14]
East Lansing, MI, USA	Minneapolis, MA, USA	Sacramento, CA, USA	[14]
San Luis Obispo, CA, USA	NA	Atlantic City, NJ, USA	[48]
San Luis Obispo, CA, USA	NA	East Lansing, MI, USA	[48]
San Luis Obispo, CA, USA	NA	Clemson, SC, USA	[48]
San Luis Obispo, CA, USA	NA	Gainesville, FL, USA	[48]
San Luis Obispo, CA, USA	NA	Washington, DC, USA	[48]
East Lansing, MI, USA	Detroit, MI, USA Tokyo, Japan	Bangkok, Thailand	[14]
East Lansing, MI, USA	NA	Valencia, Spain	[64]
Stockholm, Sweden	Oslo, Norway	New York, NY, USA	[50], [53]
San Luis Obispo, CA, USA	NA	Berlin, Germany	[48]
San Luis Obispo, CA, USA	NA	Beijing, China	[48]
San Luis Obispo, CA, USA	NA	Melbourne, Australia	[48]
San Luis Obispo, CA, USA	NA	Rio de Janeiro, Brazil	[48]
Southeastern USA			[65]
San Francisco. CA, USA (tarmac dollies)			[51]
Vatry, France (tarmac dollies)			[52]

6.1.3.2. Means of transportation

The models of aircraft were only identified in a few studies, mostly to provide some form of correlation with the vibrations generated by the propulsion engines.

For example, in a 1971 study [66], the maximum vibration amplitude recorded was at 68 Hz in a Lockheed Martin C-130 and at 48 Hz in a Douglas C-133, which corresponded to the blade passage frequency. In more recent air freight transportation environmental condition studies, only the routes or the departure and arrival airports were referenced.

Table 6.2: List of aircraft referenced in air freight environmental condition studies

Manufacturer	Model	References
Lockheed Martin	C-130 Hercules	[66], [61]
Douglas	C-133 Cargomaster	[66], [61]
Aero Spacelines	Super Guppy	[61] (data not available)
Lockheed Martin	C-5A Galaxy	[67] (compilation of review papers)
Lockheed Martin	C-141 Starlifter	[67] (compilation of review papers)
Boeing	707	[66], [67] (compilation of review papers)
Boeing	747 Combi	[50]
McDonnell Douglas	DC-9	[14]
Airbus	A320	[14]
Aero Commander	Commander AC90	[65]

Earlier transportation environmental condition studies were carried out using military aircraft in order to understand the mechanical environment of the freight. Only recent transportation environmental condition studies specify the names of the carriers used for their environment analysis (see Table 6.3). These recent studies also specify the type of door-to-door shipping service being used to assess differences.

Table 6.3: List of carrier companies subject to studies

Carrier	Type of shipping	Reference
DHL	Next day Air Shipping	[38], [63]
DHL	Second day Air Shipping	[38]
Fedex	Next day Air Shipping	[38], [63]
Fedex	Second day Air Shipping	[62], [38]
UPS	Next day Air Shipping	[38], [63]
UPS	Second day Air Shipping	[38]
USPS	Next day Air Shipping	[38]
USPS	Second day Air Shipping	[38]

It was found that different reported performance parameters could lead to different comparative conclusions. For instance, past studies indicate that DHL is 24% less severe than domestic USA handling environment. Occurrence indicators were defined as the percentage of all drops below a certain height. When using a 95% occurrence level, no significant difference can be made between DHL and FedEx, nor with the presence of warning labels. However, when using a 99% occurrence level, it shows that DHL has a better handling of packages with warning labels than FedEx.

6.1.3.3. Package sizes

Environmental assessments were carried out using various sizes of packages and even envelops with different types of cushioning. In addition, a few studies focused on pallets, measuring the shock and vibration on the pallet frame as well as on the boxes located in the centre and the boxes located in the corner of the stack [50], [53], and [31].

Table 6.4: Size of packages that have been studied

Length (cm)	Width (cm)	Height (cm)	Weight (kg)	Cushion	References
19	18	13	0.86	Polystyrene foam	[62]
21	21	16	1.011	Polystyrene foam	[62]
27	26	21	1.68	Polyurethane foam	[62]
32	31	26	2.17	Polyurethane foam	[62]
37	36	31	2.49	Polyurethane foam	[62]
56	38	25	7.5	Polystyrene foam	[31]
36	34	34	6.5	Polyethylene foam	[64]
30	30	30	1.42	Corrugated inserts	[14]
14	11	6	0.12	Corrugated inserts	[14]
27.3	18.4	NA	0.24	Bubble envelope	[47]
26.7	18.4	NA	0.28	Cardboard envelope	[47]
14.3	11.1	6.05	0.3	Polyethylene foam	[47]
36.1	31.1	21.5	NA	Aluminum frame	[48]

Noticing gentler handling for smaller packages, it was found that under a certain size, packages were put in postal bags for faster handling. Friction amongst boxes and letters would damper the shocks and vibrations experienced by the postal bag.

It was also found that pallet frames are experiencing higher amplitude of shock and vibration than boxes stacked on them.

6.2. Assessment results

6.2.1 Air transportation

Data related to the outer package such as compression, puncture and abrasion was measured in only one review paper [67]. The compressive loads are comprised of a static load (resulting from stacking boxes on top of each other) and a dynamic load (resulting from vibration during transportation). Dynamic load amplification can occur when vibrations are within the resonance frequency of the stack of boxes (six fold amplification for corrugated cases were reported). There are also additional quasi-static loads resulting from low frequency motions of aircraft. This resulted in only minor damage consisting of punctures and abrasions that did not create a hazard.

Temperature, pressure and humidity were routinely measured in the environmental evaluation studies. Pressure data helped retrace the shipment history by identifying the flight periods during the transportation cycle.

As previously mentioned, a study carried out by Singh et al [14] summarizes the data collected from 52 flights using cargo aircraft and 8 flights using passenger aircraft. This study showed that the pressure measured inside the cabin of passenger aircraft was not significantly different from the pressure measured inside the cargo hold. The highest pressure equivalent altitude was 17,454 ft (5,320 m) with a temperature range of 15.7-23.9°C, which is more strenuous than the testing standard ASTM D6653-01 (see Figure 6.3 [14]).

Shocks and vibrations were measured in all the studies selected for this review. It is important to know that these mechanical parameters are measured using tri-axial accelerometers. Hence, shocks are often reported directly in terms of acceleration. Other studies report shocks by calculating a free-fall height based on the period of time between zero acceleration and peak acceleration. The free-fall height is a well-established measurement in various standards. On the other hand, the direct acceleration data depends significantly on the apparatus and the configuration used for the measurements. Vibrations are typically reported using power density spectra in the range of 1 to 250 Hz [48].

It is generally accepted that the level of shock and vibration that freight is exposed to on board airplanes is lower than any other phase during the transportation cycle. However, in Trost's study [50], acceleration values ranged from 0.08 $m.s^{-2}$ when taxiing to apron to 0.42 $m.s^{-2}$ during touchdown. This is clearly in the same range than measurements reported in the same study for the transport to ramp and aircraft, with accelerations ranging from 0.08 to 0.51 $m.s^{-2}$.

During the whole transportation cycle, the maximum drop height recorded was 2.15 m in a domestic delivery within the USA. However, 99% of the falls occurred from a 1.26 m height (see Table 6.5).

Table 6.5: Reported drop heights in Air Freight handling

Maximum drop height (m)	Drop height at 99% occurrence (m)	References
1.85	1.45	[62]
1.87	1.86	[38]
1.24	1.06	[64]
1.22	NA	[47]
2.15	1.26	[48]
1.93	1.54	[48]

In a recent study by Singh et al [48], the numerous measurements carried out showed that the existing power density spectrum used for laboratory validation of air and truck transportation (ASTM 4169) were not representative of the actual measurements. The authors proposed a new spectrum that raises the power density in the range of 20 to 60 Hz (see Figure 6.1 [48])

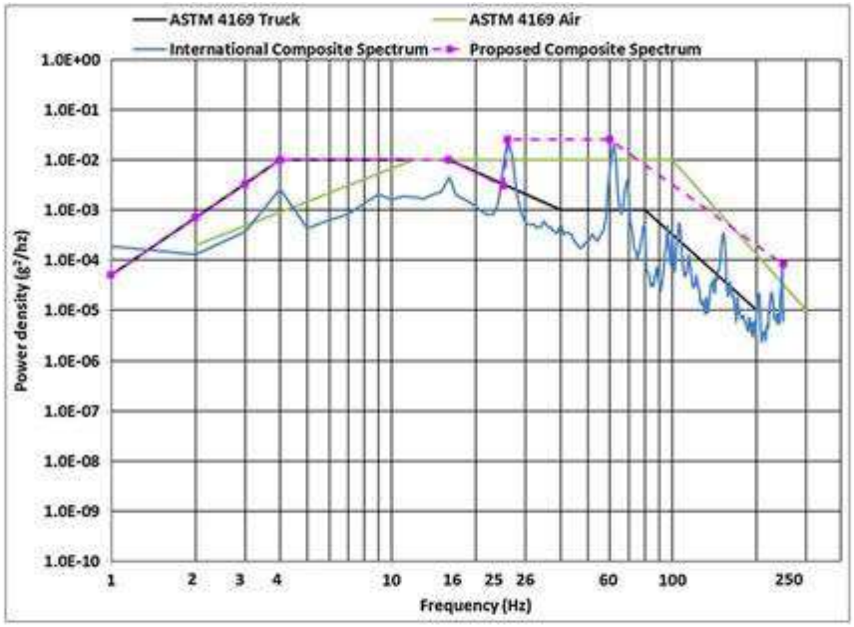

Figure 6.1: Power density spectrum with proposed spectrum for laboratory analysis [48]

7. KEY FINDINGS

Shipping by air involves different modes of transportation. For example, a truck will pick up the product, the truck moves the product to the airport, and the freight is processed and loaded onto an airplane. At the destination airport, the freight is removed from the airplane, processed, loaded onto a truck, and moved to final delivery.

Every mode of transportation exposes packages to environmental and mechanical stress hazards but at various levels. These hazards are: pressure, humidity, temperature, air quality, shock, drop (or fall), vibration, impact and crush.

UN Transport of Dangerous Goods (TDG)

Table 7.1 shows a comparison of the UN TDG 38.3 test standards and the conditions experienced by air transported freight according to previous studies. Tests 5, 7 & 8 are tests involving the resistance of the battery to electrical malfunction or failure. These are secondary effects of environmental or mechanical stresses and would occur as the result of excessive environmental or mechanical stresses or improper packaging to protect against such stresses. The risk of the failure mechanisms tested for in UN 38.3, with the exception of altitude and thermal cycling, could be reduced, but not eliminated, through the use of adequate packaging.

Table 7.1: Comparison of UN TDG 38.3 test standards and measured shipping stresses.

Stress	UN TDG test	Test Conditions[1]	Conditions Experienced	Reference
Altitude	38.3.4.1	11.6 kPa (~50,000ft), 6 hrs	51.3 kPa (~17,500ft)	[14]
Thermal Cycling	38.3.4.2	-40°C to 85°C, 6hrs at max, 10 cycles[2]	-29°C to 60°C	[33]
External Short Circuit	38.3.4.5	< 0.1 ohm, 55°C	~ 0 ohm, "Container Rain"	[32]
Shock	38.3.4.4	150g, 18 x 6ms pulse	13.11 g	[47]
Drop	N/A	1.2m drop, on edge[3]	2.1 m drop	[48]
Vibration	38.3.4.3	7 to 200 Hz, 12 x 15min	20 to 60 Hz	[48]
Crush	38.3.4.6.3	13 kN, 1.5 cm/s, between flat plates	Crushed by forklift	[54]
Impact	38.3.4.6.2	9.1 kg mass dropped, 61 cm height, 15.8 mm bar on sample	Crushed by forklift	[54]
Overcharge	38.3.4.7	2X maximum current, 24 hrs	N/A	
Forced Discharge	38.3.4.8	Discharge time = capacity / initial current	N/A	

[1] The most severe test conditions from all testing standards, UN TDG test conditions unless otherwise specified.
[2] Test conditions for IEC 62660.
[3] Test conditions for IEC 62281.

Pressure / Altitude

During the cell life cycle there will be a pressure differential between the cell interior and the environment depending on the type of cell, manufacturing process, factory location, and where and how the cells are shipped and used. Also, some types of lithium ion cells are more sensitive to environmental pressures (e.g., pouch cells). The altitude tests require holding the cells or batteries to a pressure equivalent to 50,000 ft. There is no requirement for extended testing, pressure cycling, or testing fully discharged rechargeable cells, with the exception of ANSI C18.2M.

Humidity

Transporting goods by ship from a hot and humid environment, such as tropical regions, and delivering them in cold regions, or just transiting through these cold regions, will expose the goods to a phenomenon known to the industry as “cargo sweat” or “container rain”. Prolonged exposure to condensation resulting from temperature fluctuations in humid environments, especially in salt environments, may corrode the lithium battery headers in cylindrical cells creating the potential for external shorts. The standards reviewed specify to store cells and batteries in cool, well ventilated and dry conditions away from rain, moisture, and humidity.

IEC 60068-2-30 addresses storage and transportation in high humidity conditions and the suitability of the packaging for this. IEC 61427-1 limits the relative humidity for lithium battery storage to 90% with a maximum storage period of 12 months.

Corrugated boxes absorb moisture fast enough to temper humidity during slow changes in temperature while at sea, hence reducing the cargo sweat, but potentially transferring the humidity to the goods. The IEEE 1625-2008 standard for multi-cell mobile computing device batteries addresses insulating materials resistance to moisture.

Some battery standards meant for road vehicles have some construction requirements addressing high humidity environments to prevent pack enclosure corrosion or water absorption by insulating materials. Only cell or battery standards for road vehicles appear to have a dewing test or a humidity moisture exposure or a salt spray test to address humidity but this is meant to address operating conditions.

Temperature

If a shipping container is in direct sunlight the temperature of the batteries stored inside the container can rise to more than +60°C. At London’s Stansted Airport, temperatures peaked at 37.3°C in the summer of 2003 and the temperature on the tarmac can reach 80°C. Tarmac and aircraft off-loading and transporting to terminal can take 2-10 h.

Vibration

The level of shock and vibration that freight is exposed to on airplanes is lower than at any other phase during the transportation cycle. The existing power density spectrum used for laboratory validation of air and truck transportation (ASTM 4169) were not representative of the actual measurements and a new spectrum in the range of 20 to 60 Hz was previously recommended [14].

Shock

The highest recorded shock events occurred when packages were being handled. The package drop tests from the IEC, IEEE, UL, and the IATA Packing Instructions do not allow for a battery observation period after the drop test. The standards (UL 1642, UL 2580, ANSI C18.2M Part 2, UN TDG §38 and others) have other mechanical tests which would only be applicable if the protection provided by the packaging fails. These additional mechanical tests include the crush and impact tests.

The IATA Packing Specifications and Performance Tests of the Dangerous Goods Regulations include a stacking test (section 6.6.2) designed to ensure that the packages can withstand the compression of stacking boxes on top of each other. The equivalent force is the weight of loaded boxes seating on top of the test box for a total height of 3m.

Human Factors

Mental and physical fatigue from airport staff combined with the time sensitive nature of cargo delivery can easily lead to mishandling of cargo packages and shortcuts taken in handling procedure; leading to excessive shock on cargo. There are numerous examples of human error in cargo handling at airports that led to catastrophic loss of property and life.

State of Charge (SoC)

Estimating the SoC is complicated because there is no standard SoC measurement protocol, and there are many variables that affect the measurement (e.g., temperature). Lithium ion batteries are more stable at lower SoC. When it comes to fire safety, the available heat during thermal runaway includes the electrical energy (SoC) plus the heat of combustion of the flammable materials; therefore, the lower the SoC, the lower the energy that is available during a thermal event.

8. CONCLUSION

The existing battery certification and shipping standards reviewed address most of the hazards that batteries are exposed to during the transportation cycle. However, the compliance scheme for Section 38.3 of the UN Tests and Criteria that exists today is self-declaratory and shippers may error due to lack of oversight. Appropriate, standardized procedures for the safe handling and transporting lithium batteries are required to avoid incidents. It will require a collaborative effort by all parties including airlines, airplane manufacturers, regulatory agencies, battery producers, package manufacturers and airports, to formulate these protocols and insure their compliance. Procedural oversight and engineering controls can be built in to minimize the potential for serious incident, but ultimately, it is down to the individual if they choose to follow the protocol or not and incidents may occur as a result.

The altitude test up to 50,000 ft does cover the maximum possible altitude cargo airplanes could experience (please see Appendix C, Service Ceiling of Typical Cargo Aircrafts). Therefore, even during a de-pressurization event cells should withstand the pressure drop without producing a secondary event (cell failure).

The high temperature endurance / heating / thermal abuse tests to 130°C (170°C for lithium metal) most likely addresses the maximum temperature that lithium batteries may be expected to encounter during transportation.

The temperature cycling / thermal shock tests, with temperature extremes of -40°C and 85°C, most likely address the expected temperature fluctuations during the transportation cycle. However, some standards only do the test up to 70°C, 72°C, or 75°C.

The literature reviewed shows some discrepancies between the recorded fall heights (up to 2 m) and the 1.2 m test height prescribed by the standards. Also, it was proposed to increase the severity of the power density spectrum to better reflect the whole transportation cycle.

It is also worth to mention that some standards prescribe the evaluation of damage following shock and vibration tests to be done immediately after the test. These mechanical stresses can induce imperceptible damage that could evolve over time, especially when combined with other environmental stresses such as temperature changes.

9. RECOMMANDATIONS

a. Compliance verification by third parties to existing battery certification and shipping standards will mitigate the probability of error due to lack of oversight.

b. If it has not been done already, the suitability of the cells, batteries or packaging to address high humidity conditions of storage and shipping needs to be considered. E.g., adding reference to tests such as water resistance by spray method (ASTM D951).

c. It might be a good idea to quantify what it means to “fully enclose the cells or batteries” in the IATA packing instructions.

d. OCV monitoring before, right after the tests, and after a dwell time of up to 24 hours should be advised on every laboratory test.

e. NRC is not aware of specific tests for vibration or humidity for battery packaging. If the test does not exist, the vibration testing of shipping containers (ASTM D999) standard could be referenced.

f. NRC is not aware of a specific test for puncture or abrasion of battery packaging. If the test does not exist, an applicable ASTM standard could be referenced.

g. The 30% SoC requirement is difficult to enforce since SoC cannot be measured in the field. It would be very helpful to have third party factory inspections to verify the use of a reasonable Quality Assurance Program by battery shippers, which includes a protocol to determine a 30% SoC for transportation purposes.

h. Thermal testing should be done in conjunction with mechanical tests such as vibration and shock to more closely reproduce the whole transportation cycle.

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Appendix 1 Service Ceiling of Typical Cargo Aircrafts

Manufacturer	Aircraft	Service Ceiling
Airbus	A300F cargo aircraft	40.000 ft
Airbus	A300 600F	40.000 ft
Boeing	757-200	42,000 ft
Boeing	757-200PF	42,000 ft
Boeing	757-300	42,000 ft
Boeing	767-200	43,100 ft
Boeing	767-300	43,100 ft
Boeing	767-300F	43,100 ft
Boeing	747-8	43.100 ft
Boeing	747-400	45.100 ft
Boeing	747-300	45.100 ft
Boeing	747-200	45.100 ft
McDonnell Douglas	DC-8 Freighter	42.000 ft
McDonnell Douglas	DC-10-10	42,000 ft
McDonnell Douglas	DC-10-15	42,000 ft
McDonnell Douglas	DC-10-30	42,000 ft
McDonnell Douglas	DC-10-40	42,000 ft
McDonnell Douglas	MD-11CF	43,000 ft
McDonnell Douglas	MD-11F	43,000 ft
McDonnell Douglas	MD-11C	43,000 ft