A-P-T RESEARCH, INC.
AN EMPLOYEE-OWNED COMPANY

Classification and Transportation of Defective and Damaged Charge Storage Devices

Final Report

Project #46 / TA-2

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CLASSIFICATION AND TRANSPORTATION OF DEFECTIVE AND DAMAGED CHARGE STORAGE DEVICES

FINAL REPORT

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CDTS-AL003-20-00200
October 27, 2020

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ACRONYMS

ANSI	The American National Standards Institute
A-P-T	A-P-T Research, Inc.
CFR	Code of Federal Regulations
DDR	Defective, Damaged or Recalled
DoD	U.S. Department of Defense
DOT	U.S. Department of Transportation
EU	European Union
FAA	Federal Aviation Administration
FAR	Federal Acquisition Regulation
FCS	Fire Containment Systems
FOD	Foreign Object Debris
GCAA	General Civil Aviation Authority
GPS	Global Positioning System
HF	Hydrogen Fluoride
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IEC	International Electrotechnical Commission
IECEE	IEC System for Conformity Testing and Certification of Electrotechnical Equipment and Components
IEEE	Institute of Electrical and Electronics Engineers
IFALPA	International Federation of Air Line Pilots' Associations
IMDG	International Maritime Dangerous Goods
ISO	International Organization for Standardization
LED	Light-emitting diode
Li-ion	Lithium-ion batteries
MDA	Missile Defense Agency
NEMA	National Electrical Manufacturers Association
NRTL	National Recognized Testing Laboratory
OEM	Original Equipment Manufacturer
OSHA	Occupational Safety and Health Administration
PED	Portable Electronic Device
PHA	Preliminary Hazard Analysis
PHL	Preliminary Hazard List
PHMSA	Pipeline and Hazardous Materials Safety Administration
PMP	Program Management Plan
PPE	Personnel Protection Equipment
RAC	Risk Assessment Code
RESS	Rechargeable Energy Storage System
RMIS	Remote Monitoring Integrated System
SAE	Society of Automotive & Aerospace Engineers
SEI	Solid Electrolyte Interface
SMO	Source-Mechanism-Outcome
SMS	Safety Management Services, Inc.
UL	Underwriters Laboratories
ULD	Unit Load Device
UN	United Nations
Wh	Watt-hour

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PART I: INTRODUCTION

1.0 Executive Summary

Under contract with the Department of Transportation (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA), A-P-T Research, Inc. (APT), and subcontractor Safety Management Services, Inc. (SMS) researched and developed recommended methods for the classification and safe transportation of defective and damaged charge storage devices, with a focus on lithium ion (Li-ion) batteries.

The scope of the effort was development of a discrete set of products, namely:

1. Development of a classification protocol
2. Development of a recommended classification method
3. Development of recommended test methods for safe transport
4. Development of a recommended packaging standard for damaged and defective battery transportation.

These products were delivered in a series of reports. The modes of transportation of Li-ion batteries considered as part of this effort were by truck, rail, air, and water (surface vessels only). Bulk and individual quantities were both considered, as well as whether the damaged or defective Li-ion batteries entered the transportation phase with existing issues or became damaged/defective during transport.

Testing of four different container designs was performed to validate the team's proposed approach for qualifying effective containers for safing damaged and defective charge storage devices. Table 1 presents a summary of the container requirements derived by the team and an assessment of whether the prescribed testing that was performed is sufficient to evaluate whether a container meets each requirement.

Table 1: Effectiveness of Testing to Assess Candidate Containment Devices

Container Test Requirements	Effective to Assess Candidate Containment Devices
1. Ability to contain effluents	Yes
2. Ability to contain fire	Yes
3. Ability to contain fragments	Yes
4. Surfaces of the container will not reach levels that could burn personnel	Yes
5. Release of hazardous or corrosive material from the battery will be contained	Yes
6. Batteries will be secure in the container and not loose where they may contact container interior surfaces	Yes

Container Test Requirements	Effective to Assess Candidate Containment Devices
7. If multiple batteries are contained in a single container, an event from one battery will not propagate to an adjacent battery	Yes
8. The battery is protected from external contamination that could initiate or exacerbate a thermal reaction	Yes
9. Container materials are compatible with the battery, ensuring that a leak will not result in a subsequent reaction between the battery fluid and the container materials	Yes*

* This should be supported by chemical analysis performed by the manufacturer during the design stage and containers should be labeled to indicate the charge storage devices for which they are intended.

1.1 SUMMARY OF CONCLUSIONS/RECOMMENDATIONS

One of the primary findings/conclusions from this effort is that safe transport of charge storage devices that become damaged or defective in transit is predicated upon three elements:

1. Proper classification of the devices following an established classification protocol,
2. Proper handling and packaging of the devices using an appropriate classification methodology, and
3. Equipment designed to effectively control the hazards of a damaged or defective charge storage device.

The following recommendations were developed as a result of this study:

1. A recommended classification protocol that laypersons, with little to no training, can use to classify the predominant battery hazard(s) with which they are confronted, and successfully identify the steps needed to safe a defective or damaged Li-ion battery or other charge storage device for continued transport.

2. A recommended classification method, which is a simple procedure with dedicated equipment that can be used to safely mitigate or ameliorate the realization of hazards from damaged and defective Li-ion batteries or other charge storage devices when encountered during transportation.

3. To achieve the third element of the safety support structure listed above, a recommended method to determine the ability of containment equipment to effectively mitigate or ameliorate hazards from defective or damaged Li-ion batteries and other charge storage devices was developed.

4. A recommended packaging standard for defective or damaged Li-ion batteries and other charge storage devices encountered in transit, incorporating the recommended classification protocol and methods, and test methods. The recommended standard provides an itemization of features that should be included in containers chosen for use by industry.

5. A recommended path forward, integrating the findings and recommendations of this study into a safe, reliable, and effective packaging standard that will be accepted by industry and regulators.

2.0 Problem Overview

Demand for new and innovative portable and rechargeable sources of power or charge storage devices, such as lithium-ion batteries (Li-ion), has outpaced technology in many cases, or has outpaced proof of the safety of new technology before its release to the market. This has resulted in a large number of high-profile incidents from Li-ion battery failure, which led to property damage and injury. However, these kinds of problems with Li-ion batteries are not new, having existed since the earliest designs in the 1970s.

As of December 1, 2019, there have been 261 airplane/airport incidents involving Li-ion battery malfunctions since January 1, 2006. DOT PHMSA also has documentation of over 800 reported incidents caused by Li-ion batteries across all modes of transportation from 2014-2018. The list does not include an additional three major aircraft accidents where Li-ion battery cargo shipments were implicated but not proven to be the fire source.[1]

Nearly all of these events can be traced to defective or damaged charge storage devices and, in many instances, to charge storage devices that were known in advance to be defective or damaged, but for which no special precautions were taken to prevent a hazardous incident during transport.

3.0 Project Scope

The scope of the effort was defined as a discrete set of deliverables, namely:

1. ***Development of a classification protocol*** based primarily on existing classification protocols and hazards identified from a hazard analysis.
2. ***Development of a recommended classification method*** using the draft classification protocol as a basis and proven with testing and analysis, as needed. The classification method is intended to be a tool for industry to use when evaluating defective or damaged charge storage devices.

   An interim report entitled, "Classification Protocol and Method Report," outlining the findings from this task was delivered to the COR documenting the results of these efforts.
3. ***Development of recommended test methods for safe transport.*** To accomplish this, the team conducted a series of tests to validate and verify the viability of the proposed packaging solutions (methods) to enable safe transport of defective or damaged charge storage devices. The findings were delivered to the COR in a report entitled, "Revised Test Report."

[1] https://www.jdsupra.com/legalnews/new-phmsa-lithium-ion-battery-rule-52582/

4. ***Development of a recommended packaging standard for damaged and defective battery transportation.*** Draft recommendations were included in the Revised Test Report. Updated recommendations from the team and a summary of all analyses, findings, conclusions, and recommendations are included in this draft Final Report.

To accomplish these tasks, the APT/SMS Team researched and reviewed available information on defective and damaged battery hazards and packaging; performed a series of hazard analyses to identify potential hazards posed by charge storage devices; researched and reviewed existing classification protocols for these devices; and tested the viability of recommended containment methods and features to support safe transport of defective or damaged charge storage devices.

As the use of charge storage devices like Li-ion batteries becomes more common, so do the hazards associated with failure of these devices during transportation. Some of these failures have led to more serious issues, including thermal events, the release of dangerous chemicals, and violent case ruptures, all of which are difficult to control. Many of these failures are due to designs of consumer electronic devices that are incompatible with the charge storage devices they use, particularly if latent defects exist in the charge storage devices.

Like most defective or damaged hazardous materials, when these charge storage devices fail, the nature of the hazards they pose can change, as well as the probabilities associated with each of those hazards. These devices must also be disposed of safely, which usually requires transport of the damaged devices. However, the devices no longer qualify to be shipped under their original hazard classification, UN number, or proper shipping name since their hazardous properties have changed. They need to be re-classified to ensure that the precautions needed for safe handling and transport are clearly communicated. In addition, these devices need special packaging and containment during transportation to further ensure safety.

The modes of transportation of Li-ion batteries considered as part of this effort were by truck, rail, air, and water (surface vessels only). Bulk and individual quantities were both considered, as well as whether the damaged or defective Li-ion batteries entered the transportation phase with existing issues or became damaged/defective during transport.

4.0 Report Scope

This draft Final Report is the third of four deliverables in the project. It documents a recommended packaging standard for damaged and defective battery transportation and presents a summary of all analyses, findings, conclusions, and recommendations to date.

Specifically, this report summarizes the activities and findings associated with development of 1) a classification protocol based primarily on existing classification protocols and the hazards identified from hazard analyses, and 2) a classification method for safely controlling hazards associated with defective or damaged charge storage devices during transport.

The recommended classification protocol presented is intended to be a step-by-step process that can be followed by members of the public, with little to no training, to safely isolate/stow a defective or damaged lithium ion battery encountered during transportation. The method(s) applied to safely isolate/stow the devices are identified in the recommended classification method.

The recommended classification method is intended to be a simple procedure utilizing dedicated equipment that can be used by members of the public, with little to no training, to safely mitigate or ameliorate the realization of hazards from a defective or damaged Li-ion battery encountered during transportation.

The proposed method was empirically proven by a series of tests to validate and verify the viability of the proposed packaging solutions (methods) to better ensure safe transport. The series of tests conducted and the results are summarized in this report. The intent of the testing was not to endorse specific products. Instead, it was to highlight characteristics of containers that are effective to control hazards associated with defective and damaged charge storage devices and to test the viability of the proposed testing protocol.

Reports previously delivered under this effort include:

- Classification Protocol and Method Report
- Revised Test Report

Their content is aggregated in this report.

PART II: RESEARCH AND ANALYSIS

5.0 Research

Research performed for this effort focused on four primary areas: battery accident history, identification of potential accident scenarios, existing classification protocols for damaged devices, and existing classification methods for damaged devices, to include those enumerated in 49 CFR 173.185. The APT/SMS Team initially researched these topics without regard to the phases of a Li-ion battery's life cycle in which incidents or accidents have been encountered. This was done to better ensure a thorough knowledge and understanding of the nature of hazards associated with Li-ion batteries. Research and analysis of the data obtained was then narrowed to focus on how it applied specifically to the transportation phase.

Using this research as a foundation, a preliminary protocol and method for safely controlling hazards associated with defective or damaged Li-ion batteries during transport were developed.

5.1 ANATOMY OF A BATTERY

The team's research identified that, in general, there are two primary reasons for Li-ion battery failures. The first involves design flaws, often involving an electrode, separator, electrolyte, or a failure involving assembly processes. This was documented by multiple sources as the primary contributing cause of the highly publicized incidents involving Samsung Note 7 phones.[2] The second reason is associated with environmental stresses on the batteries, including charging at sub-freezing temperature, vibration, or shock/impact. In addition, an underlying contributing factor is that Li-ion batteries contain a large amount of energy in a compact package, which is one of the key reasons they are used in a wide variety of applications, from cellular phones to electric cars.

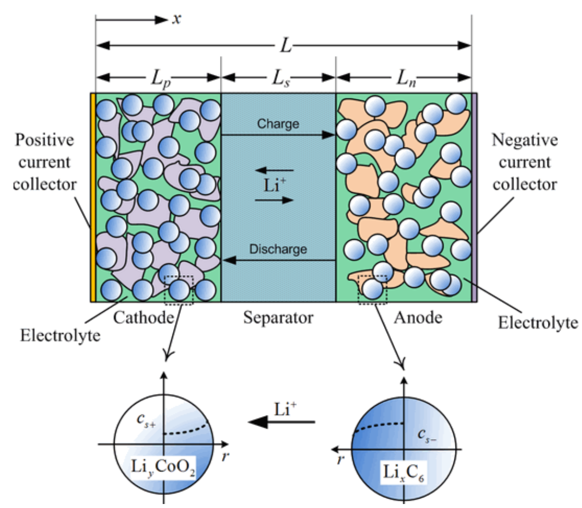

Figure 1: Electrochemical Model of a Li-ion Battery[2]

A Li-ion battery has an energy density of up to approximately 160 watt hours per kilogram (W-h/kg), roughly twice that of a fresh alkaline battery or a nickel-cadmium (NiCad) rechargeable battery. To produce that power, it relies on three main components: the positively charged

[2] https://www.consumerreports.org/safety-recalls/why-lithium-ion-batteries-still-explode-and-whats-being-done-to-fix-the-problem/

cathode, which is made of metal oxide, the negatively charged anode, which is made of graphite, and the liquid electrolyte (a solvent containing lithium salts) that enables the electric charge to flow between the two poles.

To function properly, the cathode and anode need to be physically separated. Li-ion batteries accomplish that with a permeable polyethylene separator, which can currently be as thin as 10 microns. As batteries improve and engineers attempt to pack more power into a smaller package, thinner plastic separators are used, often being taxed to their limits.

When the separator is breached, it causes a short circuit, which starts a thermal runaway process. The chemicals inside the battery begin to heat up, which causes further degradation of the separator, and the battery can eventually reach temperatures of more than 1,000 °F. At that point, the flammable electrolyte can ignite or even explode when exposed to oxygen in the air.

Another common source of failure in Li-ion batteries can be attributed to charge/discharge cycles. Over the course of multiple battery charge/discharge cycles, particularly when the battery is cycled at a fast rate, microscopic fibers of lithium sprout from the surface of one of the lithium electrodes and spread across the electrolyte until they reach the other electrode. An electrical current passing through these dendrites can short-circuit the battery, causing it to rapidly overheat and possibly catch fire.

There are usually several stages to a battery failure. These include off-gas generation, which provides a consistent and early warning of battery failure. Mitigating actions performed at this stage, such as venting and allowing the seal to rupture, can prevent other battery failures. If not addressed, off-gas generation can be followed by smoke generation and fire generation, which are often simultaneous.

These and other failure scenarios were identified and evaluated as part of the research and analysis phase of the team’s activities.

5.2 BATTERY ACCIDENT HISTORY

Following is a description of some of the more prominent and relevant Li-ion battery accident events that the team identified. They are included primarily to provide context for the types of hazards realized when Li-ion batteries are defective or become damaged.

General. In 2006, Sony recalled millions of Li-ion battery packs after several hundred caught fire in Apple and Dell laptops. The root cause was traced to microscopic metal particles in the recalled battery cells that could contact other parts of the battery cell, leading to a short circuit within the cell. Typically, battery packs are designed to simply power off when a cell short circuit occurs. However, as explained in the findings of the investigation, under certain rare conditions, an internal short circuit may lead to cell overheating and either flames or rupture (an explosive event).[3]

[3] https://batteryuniversity.com/learn/archive/lithium_ion_safety_concerns

Electric cars. Numerous electric vehicles like the Tesla Model S have experienced incidents involving hazardous Li-ion battery failures. As a couple of examples, Tesla Model S vehicles caught fire in Norway in 2016 and in Belgium in 2019 while plugged into Tesla Superchargers. In both cases, the fire resulted in complete destruction of the car.[4,5] In another incident, the battery pack of a Tesla Model S in Los Angeles caught fire. The owner said that the fire started "out of the blue" without any impact while the vehicle was being driven in traffic. At the time of this report, Tesla has said that it is investigating the situation.[6] Numerous other vehicle fires have been attributed to battery failures.

Rail. In April 2017, a shipment of Li-ion batteries on a Union Pacific railcar caught fire and exploded outside of Houston, TX. The blast from the explosion was large enough to blow out the windows of a nearby building and cause other damage. After the explosion, a fire, described by witnesses as an inferno, broke out, taking fire fighters hours to extinguish. The cause was identified to be multiple 55-gallon drums loaded with Li-ion batteries. The drums, which were transported without lids, were being shipped to a recycling facility.[7]

Another Li-ion battery/rail incident happened in September 2017 when a railcar container was observed to have smoke emitting from it. The cause of the fire was a drum of used lithium-ion batteries that were not packaged for transport according to regulations and caught fire due to a chemical reaction.[8]

Marine. No maritime incidents involving transportation of Li-ion batteries were found during the team's research. One incident involving a Li-ion battery was recorded on the tugboat Campbell Foss, where the battery in use on the tugboat caught fire as result of a software issue that allowed the battery to enter an overcharged condition. However, this event was when the battery was in use and not during transport of the battery.[9]

Cargo aircraft. Several incidents involving hazardous Li-ion battery failures have been experienced during cargo aircraft ground and flight operations.

In 1999, lithium ion batteries were credited with causing a fire at the Northwest Airlines cargo facility at Los Angeles International Airport.[10]

On August 7, 2004, a fire attributed to Li-ion battery failure destroyed freight in a unit load device (ULD) at the Federal Express cargo hub in Memphis, TN. The ULD, which contained Li-ion batteries, had been raised on loading equipment and pushed about halfway onto an airplane

[4] https://electrek.co/2016/01/01/tesla-model-s-caught-fire-and-burned-down-charging-supercharger/
[5] https://electrek.co/2019/06/01/tesla-fire-supercharger/
[6] https://electrek.co/2018/06/16/tesla-model-s-battery-fire-investigating/
[7] https://www.click2houston.com/news/2017/04/24/lithium-batteries-causes-train-car-explosion-in-ne-houston/
[8] Information was provided by PHMSA for this incident
[9] https://www.maritime.dot.gov/sites/marad.dot.gov/files/docs/innovation/meta/9616/hybrid-battery-refit-final-report-pics.pdf
[10] https://www.federalregister.gov/documents/2007/08/09/E7-15213/hazardous-materials-transportation-of-lithium-batteries

bound for Paris, France, when loading personnel reported smelling smoke. They returned the smoking ULD to the loading equipment and lowered it to the ground. When fire department personnel opened the ULD, a fire flared up inside.[11]

In 2010, the flight crew of UPS Airlines Flight 6 reported a fire in the cockpit in-flight shortly after takeoff from Dubai International Airport. They attempted to return the Boeing 747-400F to Dubai but, due to smoke in the cockpit limiting visibility, crashed, killing both crewmembers. The final investigation report from the United Arab Emirates General Civil Aviation Authority (GCAA) stated that the fire was caused by autoignition of the contents of a cargo pallet, which contained "a significant number" of lithium-type batteries and "other combustible materials."[12]

In addition to these three high profile incidents, as mentioned earlier, hundreds of aviation incidents that have occurred involved, or are suspected to have involved, lithium batteries. Three aircraft accidents where lithium batteries were known to have been on board as cargo are summarized in Table 2, including UPS Airlines Flight 6.

Table 2: Summary of Three Aviation Accidents[13]

	Boeing 747-400 Jeju	Boeing 747-400 Dubai	DC-8 Philadelphia
Li batteries on board	Yes	Yes	Yes
Declared as cargo	Yes	No	Lithium – Yes Other items – No (not considered to be a factor)
Hull loss	Yes	Yes	Yes
Fatalities (%)	2 (100%)	2 (100%)	0 (0%)
Phase of flight	Early cruise	Early cruise	Descent
Time into flight	50 minutes	22 minutes	c. 2 hours
Time to uncontained fire	17 minutes	23 minutes	27 minutes

Several important facts are shown in this table. For all three incidents, once there was a fire, particularly with a large quantity of lithium batteries, the time from ignition to an uncontrollable fire can be quite short – 17 minutes, 23 minutes, and 27 minutes, respectively. However, it must be noted that each of these incidents included large quantities of lithium metal and/or lithium ion batteries. Recent regulatory changes have limited the amounts and the manner in which they are carried.

For the Jeju incident, the fire broke out in the cargo area where dangerous goods, including lithium batteries, were stored. For the Dubai incident, it was found "with reasonable certainty"

[11] https://www.ntsb.gov/investigations/AccidentReports/Reports/HZB0501.pdf

[12] https://www.gcaa.gov.ae/en/ePublication/admin/iradmin/Lists/Incidents%20Investigation%20Reports/Attachments/40/2010-2010%20-%20Final%20Report%20-%20Boeing%20747-44AF%20-%20N571UP%20-%20Report%2013%202010.pdf

[13] ansondg.net/downloads/file_Lithium_battery_accidents.pdf

that the fire that caused the crash originated in a cargo container that held thousands of lithium batteries. For the Philadelphia incident, it is believed that the fire started elsewhere in the cargo hold and spread to the lithium batteries.

Passenger aircraft. In 2013, two incidents occurred five days apart at Boston's Logan International Airport and Narita International Airport in Tokyo, Japan, involving smoke and flames from Li-ion batteries used in auxiliary power units of new Boeing 787 Dreamliners. Firefighters extinguished the flames with Halotron, a fire suppressant, but the batteries later reheated and rekindled. The mechanism of failure leading to the incident was that the batteries hissed, leaking electrolyte, and ruptured. Again, the reason was reported as thermal runaway. As a result of these two events, the U.S. FAA grounded the entire Boeing 787 Dreamliner fleet. Note that these events occurred when the batteries were in use and not being transported.[14]

A Samsung Note 7 cell phone caught fire in October of 2016, causing Southwest flight 994 to be evacuated during the boarding process. The user of the phone said he powered down his phone for flight when it started to overheat, which led to a series of popping sounds and smoke emitting from the phone. This phone had previously been identified by Samsung as a "safe" variant after an initial recall had already been issued. In January of 2017, Samsung released a statement explaining that it had narrowed the issue down to the design of the battery itself. The negative electrode of the battery was able to contact the positive electrode due to insufficient insulation and separation. This caused a short circuit, which could devolve to thermal runaway.[15] As of this writing, there have been 96 reports of Samsung Note 7 batteries overheating in the United States, including 23 new reports after the first recall of the Note 7. Overall, Samsung Note 7 batteries were reported to have caused 13 burn injuries and 47 reports of property damage.[16]

Table 3 presents a sample of aviation incidents that involved lithium batteries. These incidents were cited in a study performed on the feasibility of improving safety during transportation by storing lithium batteries at very low states of charge.[17] It shows some of the mechanisms by which Li-ion battery hazardous conditions can be realized and was considered by the APT/SMS Team when identifying which hazard causes are most credible.

Table 3: Sample of Aviation Accidents (2004-2011)

Time	Incident	Identified Root Cause
Oct-2011	Asiana airlines Cargo flight, a Boeing 747-400F, registration HL7604, crashed due to an in-flight fire in cargo bay.	Physical evidence did not permit identification of the exact cause of fire. However, the fire started near pallets where lithium-ion batteries were being stored.

[14] https://www.scientificamerican.com/article/how-lithium-ion-batteries-grounded-the-dreamliner/
[15] https://www.usatoday.com/story/news/2016/10/05/samsung-galaxy-note-7-explodes-whileboarding-southwest-flight/91602698/
[16] https://www.digitaltrends.com/android/samsung-halts-galaxy-note-7-shipments-phones-catching-fire/
[17] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5505962/

Time	Incident	Identified Root Cause
Sep-2010	UPS Airlines Flight 6, a Boeing 747-400F, registration N571UP, crashed due to an in-flight fire in cargo bay.	The fire was caused by auto-ignition of the contents of a cargo pallet, which contained “a significant number” of lithium-ion batteries and other combustible materials
Aug-2009	FedEx discovered a burning and smoking package of GPS tracking devices containing lithium-ion batteries at one of their facilities. Two of the devices had heated causing surrounding packaging and cushioning to ignite. The fire was extinguished, only to reignite hours later.	Mechanical shock/vibration, external short circuit, and improper packaging
Aug-2009	UPS found a smoldering package containing lithium batteries at its Taiwan hub. Inspection of other packages in the same consignment indicated that similar batteries were shipped without terminal protection.	External short circuit, mechanical shock/vibration and improper packaging
July-2009	At the UPS hub in the Dominican Republic, a box started to emit smoke. The package had Li-ion batteries for mobile phones.	External short circuit of the Li-ion batteries due to improper packaging
Aug-2008	UPS discovered a smoking package containing Li-ion battery-powered LED lamps at a ground sort facility.	External short circuit brought about by a combination of transport and handling shock and vibration with improper packaging
Dec-2007	Package containing a toy helicopter kit with Li-ion polymer batteries was discovered emitting smoke at a FedEx sort facility.	External short circuit brought about by a combination of transport and handling shock and vibration with improper packaging
Sept-2007	At a FedEx facility, a package of lithium-ion batteries was emitting smoke but the fire was contained within the box.	Mechanical damage
Jun-2007	A cargo hold fire alarm was activated during taxiing. The source was a package of Li-ion batteries.	External short circuit
Aug-2004	A box containing Li-ion battery modules for a prototype EV started to emit smoke on a FedEx cargo plane loading ramp.	External short circuit

Over 100 other transportation-related incidents, not discussed in this report, have been reported involving Li-ion batteries. These incidents involve transport by land and air, and were used as part of the basis for development of the Preliminary Hazard List (PHL) and Preliminary Hazard Analysis (PHA).

5.3 IDENTIFIED POTENTIAL ACCIDENT SCENARIOS

Numerous potential accident scenarios involving damaged and defective Li-ion batteries have been identified and are compiled in Table 4. This is considered to be a preliminary list since it does not include hazards related to a specific transportation system or charge storage device design.

Table 4: Potential Accident Scenarios

Number	Accident Scenario	Example
1	Crushed on aircraft in passenger area	Passenger loses phone in airline seat then reclines seat, crushing phone while looking for it.
2	Crushed on aircraft in cargo area	Passenger traveling with loose batteries in luggage and items shift from turbulence.
3	Crushed during ground transport	Battery is crushed while going through sorting facility.
4	Crushed during sea transport	Pallet in shipping container is not properly tied down and falls onto box full of batteries.
5	Short on aircraft in passenger area	Passenger traveling with loose batteries in backpack where a short happens with shifting items.
6	Short on aircraft in cargo area	Passenger traveling with loose batteries in luggage.
7	Short during ground transport	Batteries loosely packaged and shift during transport.
8	Short during sea transport	Batteries loosely packaged and shift during transport.
9	Swelling on aircraft in passenger area	Battery is over charged.
10	Swelling on aircraft in cargo area	Battery is manufactured with a defect and not detected by quality control.
11	Swelling during ground transport	Battery is manufactured with a defect and not detected by quality control.
12	Swelling during sea transport	Battery is manufactured with a defect and not detected by quality control.
13	Thermal runaway on aircraft in passenger area	Power bank over-discharges.
14	Thermal runaway on aircraft in cargo area	Battery is counterfeit or an inferior design.
15	Thermal runaway during ground transportation	Battery is over charged.
16	Thermal runaway during sea transportation	Battery is over charged.
17	Puncture on aircraft in cargo area	Passenger traveling with loose batteries in luggage and items shift from turbulence.
18	Puncture during ground transport	Forklift punctures pallet of batteries being loaded for transport.
19	Puncture during sea transport	Forklift punctures pallet of batteries being loaded for transport.

Number	Accident Scenario	Example
20	Electrolyte leak on aircraft in passenger area	Tablet has failing chip installed that causes the tablet to cycle on and off repeatedly.
21	Electrolyte leak on aircraft in cargo area	Battery is manufactured with a defect and not detected by quality control.
22	Electrolyte leak during ground transport	Box with device falls off transfer vehicle and is run over.
23	Electrolyte leak during sea transport	Saltwater moisture corrodes terminals.
24	Fire on aircraft in passenger area	Phone is charged using a defective charger.
25	Fire on aircraft in cargo area	Laptop in luggage bag falls off cargo loading belt.
26	Fire during ground transport	Batteries loosely packaged and shift during transport.
27	Fire during sea transport	Batteries loosely packaged and shift during transport.

From the team's research, the most likely failure mechanisms to occur are short circuit, swelling, thermal runaway, puncture, and crushing of a battery. The most likely hazardous outcomes include overheating, fire, rupture, and electrolyte leakage, along with associated secondary hazards.

In Table 4, examples are given of how the accident scenario may occur. The root causes (sources) of these examples range from human error to equipment failure or manufacturing defects. However, regardless of the source of the damage or defective condition, the vast majority of incidents follow a similar path (mechanism) to realization of a hazard (outcome); namely, thermal runaway.

Thermal Runaway

Thermal runaway is defined as a condition in which the heat from a failing cell causes itself and surrounding cells to fail, which thereby generates more heat. Left unchecked, it can lead to fire and/or rupture of the battery.

Thermal runaway has been demonstrated to be the most likely Li-ion battery failure to pose a problem during transport, with several stages involved in the buildup to it. Each stage results in progressively more permanent damage to a cell and more potential for transportation hazards.

The first stage of events leading to thermal runaway is breakdown of the thin passivating solid electrolyte interface (SEI) layer on the anode, due to overheating or physical penetration. The initial overheating may be caused by a physical short, excessive currents, overcharging, or high external ambient temperature. Once this layer is breached, the electrolyte reacts with the carbon anode as it does during the formation process but at a higher, uncontrolled temperature. This is an exothermal reaction that drives the temperature up further. As the temperature rises, heat from the anode reaction causes the breakdown of organic solvents used in the electrolyte, releasing potentially flammable hydrocarbon gases. This has been shown to occur at temperatures as low as 70 ºC (158 ºF). The gas generation due to breakdown of the electrolyte causes pressure to build inside the cell. Although the temperature increases beyond the flashpoint of the gases released by the electrolyte, the gases do not burn because there is no free oxygen in the cell to sustain a fire.

Within the cell, at around 135 ºC, the polymer separator melts, allowing short circuits between electrodes. Eventually, heat from electrolyte breakdown causes breakdown of the metal oxide cathode material, releasing oxygen. This enables burning of both the electrolyte and gases inside the cell. The breakdown of the cathode is also highly exothermic sending the temperature and pressure higher. Cells are typically fitted with a safety vent, which allows the controlled release of gases to relieve internal pressure in the cell, thereby avoiding the possibility of an uncontrolled rupture of the cell – otherwise known as an explosion or "rapid venting" of the cell. Once the hot gases are released into the atmosphere, they can burn due to the presence of oxygen in the air.

It should be noted that a physical improvement to the construction of many Li-ion batteries includes an internal separation support between cell walls to limit the potential for issues like thermal runaway. Tests performed on batteries that contain internal supports have demonstrated that issues are generally not experienced until higher temperatures (around 1,000 ºC/1,832 ºF), at which point the copper internals melt and the heat spreads outward, again causing thermal runaway. As such, a relatively small fire source can be sufficient to start a lithium battery fire.

Also, on occasion, microscopic metal particles introduced during assembly and manufacturing processes as foreign object debris (FOD) may come into contact with a battery's cell, leading to a short circuit within the cell, which can also lead to thermal runaway, rupture, or fire. Battery manufacturers take steps to minimize the presence of such particles, but complex assembly techniques make elimination of all metallic dust a challenge.

Interestingly, modern battery cells, which often have ultra-thin separators of 24 µm or less, are more susceptible to impurities than older designs with lower amp-hour (Ah) ratings. Many older battery packages could tolerate a nail penetration test, but newer, higher-density Li-ion batteries with higher Ah ratings often ignite when undergoing the same test. Part of the reason for this may be because UL1642 Underwriters Laboratories (UL) testing no longer mandates nail penetration for safety acceptance of lithium-based batteries.

All of this is a significant concern for lithium batteries during transport, particularly when they are not in a state of stasis, but have a load placed upon them, either electrically or thermally. Also, the charge level of a battery has an impact on how it reacts when stressed. Occasionally, overheated/over-pressurized cells do not vent, but instead explode forcefully, expelling the entire contents of the cells from the casing. Regardless of the outcome scenarios, the combination of overheating/over-pressurization or thermal runaway, when combined with a lack of compatible packaging and storage can lead to development of hazardous situations during transportation.

5.4 EXISTING CLASSIFICATION METHODS FOR DAMAGED DEVICES (INCLUDING THOSE FROM 49 CFR 173.185)

There are numerous agencies, regulations, and guidance governing defective and damaged charged storage devices. A selection of the most prominent ones is presented in this section.

Although seemingly healthy Li-ion batteries that have not exhibited any indication of being defective or damaged can fail during transportation and become hazardous, only those regulations that specifically pertain to defective and damaged batteries or their identification are included.

The APT/SMS Team evaluated the impacts, differences, and solutions from each of these organizations and others as part of developing a classification protocol and method for safing defective and damaged Li-ion batteries.

5.4.1 U.S.-Based Organization and Standards

U.S. Code of Federal Regulations (49 CFR)

Following is an excerpt from 49 CFR § 173.185 - Lithium cells and batteries[18] outlining requirements for transport of Li-ion batteries known prior to shipment to be defective or damaged.

> *(f) Damaged, defective, or recalled cells or batteries. Lithium cells or batteries, that have been damaged or identified by the manufacturer as being defective for safety reasons, that have the potential of producing a dangerous evolution of heat, fire, or short circuit (e.g., those being returned to the manufacturer for safety reasons) may be transported by highway, rail or vessel only, and must be packaged as follows:*
>
> > *(1) Each cell or battery must be placed in individual, non-metallic inner packaging that completely encloses the cell or battery;*
> >
> > *(2) The inner packaging must be surrounded by cushioning material that is non-combustible, non-conductive, and absorbent; and*
> >
> > *(3) Each inner packaging must be individually placed in one of the following packagings meeting the applicable requirements of part 178, subparts L, M, P and Q of this subchapter at the Packing Group I level:*
> >
> > > *(i) Metal (4A, 4B, 4N), wooden (4C1, 4C2, 4D, 4F), or solid plastic (4H2) box;*
> > >
> > > *(ii) Metal (1A2, 1B2, 1N2), plywood (1D), or plastic (1H2) drum; or*
> > >
> > > *(iii) For a single battery or for a single battery contained in equipment, the following rigid large packagings are authorized:*

[18] https://www.law.cornell.edu/cfr/text/49/173.185

(A) Metal (50A, 50B, 50N);

(B) Rigid plastic (50H);

(C) Plywood (50D); and

(4) The outer package must be marked with an indication that the package contains a "Damaged/defective lithium ion battery" and/or "Damaged/defective lithium metal battery" as appropriate. The marking required by this paragraph (f)(4) must be in characters at least 12 mm (0.47 inches) high.

Occupational Safety and Health Administration (OSHA)

For the purposes of damaged and degraded lithium ion batteries, OSHA's role is to approve and maintain a list of National Recognized Testing Laboratories (NRTLs). A NRTL is a testing facility recognized by OSHA to have the resources and competence to provide product safety testing and certification for lithium batteries and cells. The test standards that NRTLs follow are not developed or issued by OSHA, but are issued by U.S. standards organizations, such as ANSI (the American National Standards Institute) or UL (Underwriter's Laboratories), both of which produce consensus-based product safety test standards.

Each NRTL has its own registered certification mark. Because all NRTLs are equivalent under OSHA, all NRTL marks carry the same authority and regulatory significance. They indicate that a certified product complies with specific safety requirements of the subject standard.[19]

The American National Standards Institute (ANSI)

ANSI is a private non-profit organization which develops consensus-based standards. ANSI standards are published by the National Electrical Manufacturers Association (NEMA). ANSI's C18 is a comprehensive battery standard covering general information, battery specifications, and safety standards for consumer batteries of all types (standard alkaline AA, 3A, C, D; lithium coin cells; rechargeable NiMH). ANSI's safety standards for primary and rechargeable lithium and Li-ion cells and batteries include the following:

- ANSI C18.2M, Part 2 (Portable Rechargeable Cells and Batteries - Safety Standard)[20]
- ANSI C18.3M, Part 2 (Portable Lithium Primary Cells and Batteries - Safety Standard)[21]

[19] https://www.osha.gov/dts/otpca/nrtl/nrtllist.html

[20] https://www.nema.org/Standards/ComplimentaryDocuments/Contents%20and%20Scope%20ANSI%20C18.2M,%20Part%202-2014.pdf

[21] https://www.nema.org/Standards/ComplimentaryDocuments/ANSI%20C18%203M%20Part%202%20Contents%20and%20Scope.pdf

Underwriters Laboratories (UL)

UL is an independent product safety certification organization which, in conjunction with other organizations and industry experts, publishes consensus-based safety standards. For lithium batteries, key standards are:

- UL 1642 (Lithium Batteries) – This standard is used for testing lithium cells. Battery level tests are covered by UL 2054. [22]
- UL 2054 (Household and Commercial Batteries) – For lithium batteries, UL 2054 defers all component cell level testing to UL 1642.[23]
- UL 2580 (Batteries for use in Electric Vehicles)[24]

Federal Aviation Administration (FAA)

The FAA currently forbids shipment of damaged Li-ion batteries packed by themselves (not contained in or packed with equipment) by aircraft. On their website, the following is stated in the FAA's *Fact Sheet – Lithium Batteries in Baggage*[25] (as of February 4, 2020):

> *Lithium batteries, which power everyday devices, can catch fire if damaged or if battery terminals are short-circuited.*
>
> *Devices containing lithium metal batteries or lithium ion batteries, including – but not limited to – smartphones, tablets, cameras, and laptops, should be kept in carry-on baggage. If these devices are packed in checked baggage, they should be turned completely off, protected from accidental activation and packed so they are protected from damage.*
>
> *Spare (uninstalled) lithium metal batteries and lithium ion batteries, electronic cigarettes and vaping devices are prohibited in checked baggage. They must be carried with the passenger in carry-on baggage. Smoke and fire incidents involving lithium batteries can be mitigated by the cabin crew and passengers inside the aircraft cabin.*
>
> *If carry-on baggage is checked at the gate or planeside, spare lithium batteries, electronic cigarettes, and vaping devices must be removed from the baggage and kept with the passenger in the aircraft cabin. Even in carry-on baggage, these items should be protected from damage, accidental activation, and short circuits. Battery terminals should be protected by manufacturer's*

[22] https://espec.com/na/chamber_faq/answer/UL-1642?utm_source=Redirect&utm_medium=Web&utm_campaign=Qualmark
[23] https://espec.com/na/chamber_faq/answer/UL-2054?utm_source=Redirect&utm_medium=Web&utm_campaign=Qualmark
[24] https://standardscatalog.ul.com/standards/en/standard_2580_2
[25] https://www.faa.gov/news/fact_sheets/news_story.cfm?newsId=23054

packaging or covered with tape and placed in separate bags to prevent short circuits.

Damaged, defective, or recalled lithium batteries must not be carried in carry-on or checked baggage if they are likely to be a safety concern by overheating or catching on fire. *[emphasis added]*

When in doubt, leave it out.

This is also the policy of the International Air Transport Association (IATA).

5.4.2 International Organizations and Standards

ISO/IEC 17025

For damaged and degraded Li-ion batteries, ISO/IEC 17025 certifies a quality management system for battery test labs.[26]

CE Marking

The European Union's (EU) CE marking requirements help to ensure that all safety requirements are met. CE marking is a self-declaration made by the manufacturer to acknowledge that a product meets requirements for EU product safety. The CE mark does not apply to products sold in the U.S.[27]

United Nations (UN)

The UN issues recommendations for the transport of dangerous goods worldwide. UN guidelines define test requirements for safe packaging and shipment of lithium metal and lithium ion batteries. Safety test criteria are defined in the *Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria*, Part III, Section 38.3.

UN 38.3 (also known as the T1-T8 Tests and UN ST/SG/AC.10/11/Rev. 6) covers transportation safety testing for all lithium metal and lithium ion cells and batteries. The test criteria span eight different tests (T1 - T8) and are all focused on hazards associated with transportation.

UN 38.3 is a self-certification standard. Independent third-party test lab certification is not required.

There are several additional international organizations serving the transportation industry which have their own lithium battery regulations. Although these regulations are based on UN 38.3 and DOT battery safety test criteria and rely heavily on packaging/shipping guidelines provided in 49

[26] https://www.iso.org/ISO-IEC-17025-testing-and-calibration-laboratories.html
[27] https://ec.europa.eu/growth/single-market/ce-marking_en

CFR §173.185 and §172.101, some differences regarding shipping/transportation exemptions and inclusions exist.[28] These include those published by the following:

- International Air Transport Association (IATA)
- International Civil Aviation Organization (ICAO)
- International Federation of Air Line Pilots' Associations (IFALPA)
- International Maritime Dangerous Goods (IMDG) Code

Effective 1 Apr 2016, ICAO and IATA prohibited transport of UN 3480 Li-ion batteries (Section IA, IB and II) as cargo aboard passenger aircraft. This prohibition is not applicable to batteries packed with, or contained in, equipment. Further, all UN 3480 Li-ion cells offered for transport must be at a state of charge (SoC) not exceeding 30% of their rated design capacity.[29]

The International Electrotechnical Commission (IEC)

IEC is a non-profit standards organization that writes international standards for electrical, electronic, and related technologies. IEC standards address general, safety, and transportation specifications. For lithium batteries, key standards are:

- 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)[30]
- IEC 60086-4 (Primary Batteries – Safety of Lithium Batteries)[31]
- IEC 61960 (Secondary Cells and Batteries containing Alkaline or other Non-Acid Electrolytes – Secondary Lithium Cells and Batteries for Portable Applications)[32]
- IEC 62281 (Safety of Primary and Secondary Lithium Cells and Batteries During Transport) This standard is similar to UN/DOT 38.3.[33]

The IEC System for Conformity Testing and Certification of Electrotechnical Equipment and Components is known as the IECEE. As part of its charter to facilitate international trade in electrical equipment, IECEE operates a scheme known as the CB Scheme.

The CB Scheme is an international program for the exchange and acceptance of product safety test results among participating laboratories and certification organizations around the world. The CB Scheme offers manufacturers a simplified way of obtaining multiple national safety certifications for their products. CB Test Certificates are issued by approved National Certification Bodies (NCBs) and Certified Body Testing Labs (CBTLs).

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[28] https://www.metlabs.com/industries/battery/un-lithium-battery-transportation-testing/
[29] https://blog.labelmaster.com/how-to-ship-lithium-batteries-by-air-as-of-april-1-2016/
[30] https://webstore.iec.ch/publication/32662
[31] https://webstore.iec.ch/publication/27465
[32] https://webstore.iec.ch/publication/29603
[33] https://webstore.iec.ch/publication/61994

Under IECEE, a number of IEC Standards are listed under "Category: BATT; Product: Batteries." Category BATT covers over two dozen standards.

The Institute of Electrical and Electronics Engineers (IEEE)

IEEE is an international non-profit organization covering technologies related to electricity. It develops safety standards for industry, including those for batteries. For lithium batteries, key standards are IEEE 1725 and IEEE 1625, both of which are design guidelines, not pass/fail safety standards:

- IEEE 1725 (Rechargeable Batteries for Cellular Telephones)[34]
- IEEE 1625 (Rechargeable Batteries for Multi-Cell Mobile Computing Devices)[35]

SAE International

SAE International (Society of Automotive & Aerospace Engineers) is a professional organization for the aerospace, automotive, and commercial vehicle industries. SAE develops standards for engineering professionals. With hybrid and full electric vehicles now entering the marketplace in large numbers, the need for battery standards is getting greater attention. Key SAE standards for lithium batteries include:

- SAE J 2929 (Electric and Hybrid Vehicle Propulsion Battery System Safety Standard - Lithium-Based Rechargeable Cells)[36]
- SAE J 2464 (Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing)[37]

European Union (EU) Directives

The following EU directives governing batteries have been issued:

- 2006/66/EC, EU Battery Directive (Governing batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC)[38]
- 2001/95/EC, General Product Safety (Manufacturers must also consider other directives that may apply to their product; even though apparently optional they may be of relevance to safety depending on the design, construction, and application of the battery pack)[39]

[34] https://standards.ieee.org/standard/1725-2011.html
[35] https://standards.ieee.org/standard/1625-2008.html
[36] https://www.sae.org/standards/content/j2929_201302/
[37] https://www.sae.org/standards/content/j2464_200911/
[38] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32006L0066
[39] https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32001L0095

5.5 EXISTING METHODS FOR SAFING DAMAGED DEVICES

The classification methods for damaged devices presented in Section 5.4 consist primarily of regulations and policies regarding various modes of transport that can be used for transport of defective or damaged charge storage devices and the associated logistics. In addition, there are specific precautions currently in place for Li-ion batteries to mitigate the potential for a hazardous incident during transport. The following paragraphs enumerate a few of these.

Hazard Classification

Li-ion batteries are hazard classified by DOT PHMSA as Lithium Battery Class 9 (Miscellaneous dangerous) and must be labeled accordingly, per Figure 2. Shipment of even small Li-ion batteries under UN 3480 also requires affixing the label in Figure 3 to the package, with a 24-hour emergency response telephone number on the label.

Figure 2: Lithium Battery Class 9 Placard

Damaged Li-ion batteries have specific federal packing/labeling requirements as previously outlined in 49 CFR 173.185, including use of non-metallic inner packaging, non-conductive, non-flammable, absorbent cushioning material, and special “Damaged/Defective” labels.

Figure 3: UN 3480 Lithium Battery Handling Label

Fire Extinguishing

The FAA has published a two-step procedure for battery fires on planes:

1. Use Halon to extinguish fire
2. Cool device with water

Detectors

As part of the research performed, products were identified that exist on the market to address hazards associated with damaged and defective Li-ion battery transportation. Inclusion in this report is not an endorsement or indictment of any product. In general, products available to mitigate or ameliorate hazards from Li-ion batteries that become damaged or defective while in transit are in one of two categories: detection systems and containment systems. Figure 4 shows a detection system currently available on the market.

Li-ion Tamer is a line of products designed by Nexceris to provide responders information about the condition of Li-ion batteries through monitoring for an off-gassing event from the cells. This approach is intended to provide the early warning necessary for action to be taken to prevent a battery fire or other event. The manufacturer asserts that the system is designed to detect individual cell failures without contact to the cells, enabling early action to prevent propagation as soon as a single battery cell begins to fail.[40]

Figure 4: Li-Ion Tamer AWARE Monitors[4]

Containers

Containment of Li-ion batteries is universally accepted as a viable mitigation against most Li-ion battery hazards that might be encountered during transportation.

Damaged, Defective or Recalled (DDR) Battery Containers. There are several companies that produce packaging to comply with federal regulations associated with shipping charge storage devices known in advance to be defective or damaged. These containers typically include a drum/pail with a lid and a bag of absorbent material, generally Vermiculite. Other materials used include Sorbix, Pyrobubbles, and sand.

Following are two examples of products currently on the market that are to enable safe transport of Li-ion batteries known in advance to be damaged or defective.

[40] https://liiontamer.com/

CellBlock Fire Containment Systems (FCS) sells a product called the Small DDR Lithium Battery Kit – DOT Special Permit Can. It is advertised as DOT special permit packaging designed specifically for shipping mixed lithium-ion batteries and cells, including damaged, defective, swollen, prototype, recalled, and spent units.[41]

While the special permit authorizes various types of batteries to be contained in the packaging (e.g. alkaline, nickel-metal hydride, lithium ion), there are some limitations in lithium content and Watt-hour (Wh) ratings:

Figure 5: CellBlock FCS Small DDR Lithium Battery Kit – DOT Special Permit Can[7]

- Batteries or cells of different chemistries; dry batteries; lithium-ion or metal; or used or spent batteries can be shipped within the same outer packaging as damaged batteries or cells.
- For road transport, package contents are limited to Li-ion cells or batteries with a Wh rating not greater than 60 Wh for cells or 300 Wh for batteries, or lithium metal cells or batteries with a lithium content not greater than 5 g for cells or 25 g for batteries.
- For sea transport, package contents are limited to Li-ion cells or batteries with a Wh rating not greater than 20 Wh for cells or 100 Wh for batteries or lithium metal cells or batteries with a lithium content not greater than 1 g for cells or 2 g for batteries. Transportation by cargo vessel is only permitted when motor vehicle shipments are not possible (e.g., Alaska, Hawaii, or Puerto Rico).
- When shipping or storing damaged cells or batteries, or equipment containing damaged batteries or cells, they must be individually packed in a non-metallic inner packaging (e.g., an anti-static plastic bag, fiberboard box, or foam pouch). There is no limit to the number of individual damaged cells or batteries, but no more than 5 kilograms total net weight.

Similar products by Call2Recycle are the Large and Small Damaged, Defective or Recalled Lithium Battery Kits, which are designed for safe transport of damaged, defective or recalled lithium batteries for recycling. Like the CellBlock product, Call2Recycle asserts that their

[41] https://cellblockfcs.com/product/8l-ddr-lithium-battery-kit/

products are U.S. DOT approved recycling kits under U.S. DOT Special Permit 16563. Both the large and small kits are approved to hold up to 4.4 pounds (for multiple batteries) or 5 pounds for a single battery.[42]

Figure 6: Call2Recyle's Large and Small Damaged, Defective or Recalled (DDR) Lithium Battery Kits

Containment systems for defective and damaged batteries are not new. However, with the increased attention in recent years on battery failures during transportation, several unique products have entered the market to address the issue of charge storage devices that become damaged or defective and exhibit related hazards while in transit. Most of these new containment devices can be categorized as either a box-style design or a bag-style design. Following are examples of each.

Box-Style Containers for Batteries Damaged/Defective In-Transit.

Figure 7: Flight Firebox-FXB-7 Aircraft PED Fires Containment & Extinguisher System Monitors[5]

The Flight Firebox-FXB-7 Aircraft Portable Electronic Device (PED) Fires Containment & Extinguisher System is claimed by the manufacturer as "the world's first and only aircraft PED Li-ion battery fire containment & extinguisher system, especially designed to control laptop and

[42] https://www.call2recycle.org/store/

mobile phone Li-ion battery fires on planes." It boasts a patented heat extraction and containment, multi-valve design, as well as a vented low-pressure vessel intended to minimize and arrest subsequent thermal runaway of PED lithium battery fires.[43]

Lithium Fire Guard (formerly PlaneGard) produces a fire containment case that is designed to protect people and property from Li-ion battery fires that can occur in PEDs such as laptop computers, tablets, readers, smart and cellular phones, digital cameras, and MP3 players. It advertises that it is "the only 100% containment technology available." Lithium Fire Guard is designed to fully contain and render harmless the flames, heat, smoke, toxic fumes, and flammable vapors that are associated with a PED in thermal runaway.[44]

Figure 8: Lithium Fire Guard's PG100 Fire Containment Case[6]

Lithium Fire Guard's PG100 design utilizes a transparent scoop that is also used as a shield as the fire responder approaches the burning, smoking or leaking device, providing visibility of the device while securing it.

Both of these products are designed to address the issue of encountering a damaged or defective Li-ion battery while in transit and favorably compare their effectiveness to burn bags, which typically do not contain the smoke, fumes, and vapors that might be present in an aircraft or cabin during transport and, thereby pose hazards to personnel.

Bag-Style Containers for Batteries Damaged/Defective In-Transit. Each of the devices designed to control hazards in-transit from a damaged or defective charge storage device boast unique features and capabilities. Following are three examples of bag-style containers, each of which implement different approaches to control Li-ion battery hazards.

Fire Containment Concepts produces the PED Safe-PAK, which they advertise as the only fire containment system in the industry that contains and automatically suppresses on-board lithium-ion battery fires. Figure 9 shows some of the unique features of the bag-style container. Among

[43] www.flightfirebox.com/
[44] https://www.lithiumfireguard.com/

them are filtering vents, temperature-activated suppression bladders that line the interior walls, a UL-certified fire-resistant zipper, and triple seal technology.

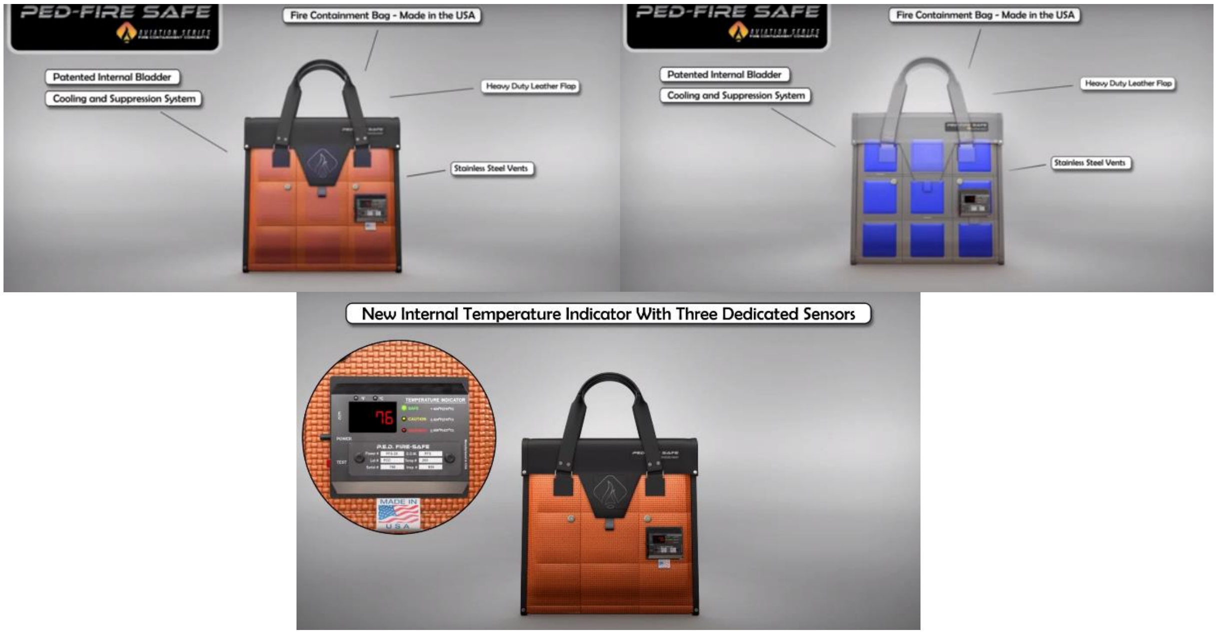

Figure 9: Fire Containment Concepts PED Safe-PAK Containment Case6

Newtex produces Z-Block™ Fire Containment Bags available in Tote-Style or Envelope-Style. The Tote-Style bag is available in one size (24" x 13" x 5") and boasts a flat bottom and 3-dimensional design that allows the bag to stand upright, two nylon carrying straps, and a zipper closure. The Envelope-Style bag is available in 2 sizes (16" x 18" or 18" x 24") and features a flat design to take minimal space, a zipper closure, and a Velcro flap. Both styles contain multiple layers of Newtex's advanced Z-Block™ Flame Retardant Fabric, ZetexPlus® Vermiculite Coated Fiberglass Fabric, and Z-Flex® Aluminized Fabric to ensure that heat and fire remain contained. The bags are designed to contain fires caused by Li-ion batteries found in laptops, cell phones, tablets, and other personal electronic devices (PEDs). Newtex advertises that their Z-Block™ fire and smoke-resistant fabrics are also used to fabricate cargo fire containment covers and exceed fire suppression performance standards set by the FAA, European Aviation Safety Agency (EASA), and leading cargo carriers. It states that the fabrics will not burn, melt, or allow flame penetration; are resistant to molten metal burn-through; will withstand temperatures up to 1,800 °F (980 °C); are watertight and chemical resistant; will not support growth of mold, fungi, and

Figure 10: Newtex Z-Block™ Fire Containment Bag

bacteria; are unaffected by extreme temperature or UV; and are abrasion, puncture, and tear resistant.

Brimstone produces a wide array of fire containment bags, smoke containment bags, and fire containment blankets, including Battery Fire Containment Bags in various sizes and styles. Brimstone asserts in their literature that their Preventer™ edition containment devices have shown in testing to contain 10,000 mAh thermal runaway events. The bags are made from patented materials that contain a layer of Kevlar in case an explosive event creates projectiles traveling at ballistic velocities. The device's carbon liner has a temperature rating of 3,000 °F, with a second layer designed to withstand temperatures above 2,200 °F for sustained periods of time. Brimstone further cites that the materials used in their bags have been FAA certified and that tests of the devices were conducted in accordance with Title 14 CFR Part 25 – Subpart D, § 25.853 (a) compartment interiors [Amdt. 25-116, 69 FR 62788, Nov 26, 2004] Appendix F to Part 25, Part I (a)(1)(ii) [Amdt. 25-111, Eff. 9/2/2003] and are FAA Compliant. The bag is designed based on the concept that rapidly expanding gases released during a Li-ion battery thermal runaway will cause a containment bag to expand like a balloon. As such, to avoid Velcro closures pulling apart and releasing potentially dangerous gases, debris, and flame, Brimstone's design incorporates a pull-over flap.

Figure 11: Brimstone Battery Fire Containment Bag - Large (Laptop) - Preventer™ Edition

Lithium Fire Guard's PG100 and a similar sized version of each of the three bag-style containment devices were chosen for testing in this study.

6.0 Analysis

6.1 PRELIMINARY HAZARD LIST

A baseline list of hazards was created, associating each with the various modes of transport. This was a collaborative effort by all members of the team, using findings from the team's research and from previous team member experience working damaged and defective battery safety. For each hazard, the assets to be protected were defined, as well as risk tolerance limits associated with each mode of transport. The team identified specific failure modes that will cause a Li-ion battery to be considered defective or damaged, as well as the effect of the failure modes. To fully characterize the hazards associated with transportation of defective or damaged Li-ion batteries, information on characteristics of the devices were considered, including critical temperatures, effects of moisture, most common failure mechanisms, and effects of exposure to other materials.

The PHL shown in Table 5 includes hazard scenarios grouped on the basis of failure type. These failure types include leaking electrolyte, outgassing, explosion, fire, thermal runaway, and electrical failure. As discussed previously in this report, thermal runaway is an intermediate mechanism for a hazard that can lead to any of the other hazard outcomes. As such, it is treated separately since it was the most common cause found by the team for battery failure.

Also of note in Table 5 is the format chosen for organization and communication of hazards in the PHL. The items in the list were identified using a Source-Mechanism-Outcome (SMO) format in order to minimize the potential for miscommunication of hazards. Following this protocol, causes that can result in different outcomes can typically be combined if the controls for the SMO-defined hazards are the same.

Table 5: Preliminary Hazard List

PHL ID	Title
1	Battery punctured through case wall leading to electrolyte leakage
2	Direct contact of a single battery cell with multiple battery cells results in cell-to-cell external short circuiting leading to battery damage causing electrolyte leakage
3	Gradual pressure buildup within cell housing due to a latent defect causes electrolyte leakage
4	Gradual pressure buildup within cell housing due to high temperature conditions causes electrolyte leakage
5	Swelling within cell pouch of a LiPo battery due to high temperature conditions causes electrolyte leakage
6	Failure of component battery is installed in/attached to causes electrolyte leakage
7	External short circuit across terminals of battery causes electrolyte leakage
8	Malfunction due to faulty battery design causes electrolyte leakage
9	Thermal runaway reaction leads to damage to the battery causing electrolyte leakage
10	Aging of battery causes weakening of cell walls leading to electrolyte leakage
11	Exposure of damaged battery cell to moisture causes leaked electrolyte to decompose into Hydrogen Fluoride (HF) resulting in corrosion and equipment damage
12	Failure of electronic protection features causes electrolyte leakage (must be in presence of another failure)
13	Incompatible battery charger causes battery damage resulting in electrolyte leakage
14	Defective battery charger causes battery damage resulting in electrolyte leakage
15	Battery punctured through case wall causes out-gassing
16	Crushing/impingement causing potential short between cell electrodes results in out-gassing
17	Dropping of a battery cell with a latent defect causing potential short between cell electrodes resulting in out-gassing
18	Dropping of battery causing potential short between cell electrodes resulting in out-gassing
19	Battery exposed to water causing a short that results in out-gassing

PHL ID	Title
20	Malfunction due to faulty battery design causes out-gassing
21	Gas emission of electrolyte by-products due to thermal runaway reaction
22	Specific to chemical composition of battery components, due to thermal runaway reaction
23	Exposure of damaged battery cell to moisture causes electrolyte decomposition into HF and out-gassing causing an inhalation hazard
24	Exposure of damaged battery cell to moisture causes electrolyte decomposition into HF and out-gassing causing corrosion and damage to nearby equipment
25	Failure of electronic protection features leads to out-gassing (must be in presence of another failure)
26	Incompatible battery charger damages battery cell resulting in out-gassing
27	Defective battery charger damages battery cell resulting in out-gassing
28	Vented gases from a damaged battery ignite
29	Direct contact of a single battery cell with multiple battery cells results in cell-to-cell external short circuiting leading to energetic rupture
30	Gradual pressure buildup within cell housing due to a latent defect causes energetic rupture
31	Explosive propagation from another battery causes energetic rupture
32	Failure of component battery is installed in/attached to causes energetic rupture
33	External short circuit across terminals of battery causes energetic rupture
34	Malfunction due to faulty battery design results in energetic rupture
35	Fragment damage from rapid battery disassembly (explosion) due to a thermal runaway reaction
36	Electrode ejection from cell casing due to thermal runaway reaction
37	Manufacturing defects of battery cell electrodes leads to energetic rupture
38	Failure of electronic protection features results in energetic rupture (must be in presence of another failure)
39	Incompatible battery charger causes energetic rupture
40	Defective battery charger causes energetic rupture
41	Battery punctured through case wall causing explosion/fragmentation (energetic rupture)
42	Crushing/impingement causing potential short between cell electrodes leads to energetic rupture
43	Battery punctured through case wall causing fire due to leaking electrolyte
44	Direct contact of a single battery cell with multiple battery cells results in cell-to-cell external short circuiting resulting in overheating and/or fire
45	Swelling within cell pouch of a LiPo battery due to high temperature conditions causes rupture
46	Propagation of overheating from another battery causes overheating and/or fire
47	Failure of component battery is installed in/attached to causes overheating and/or fire

PHL ID	Title
48	External short circuit across terminals of battery resulting in overheating and/or fire
49	Batteries dragged/excessive amount of friction applied leading to fire
50	Battery exposed to water causing a short resulting in overheating and/or fire
51	Malfunction due to faulty battery design causes overheating and/or fire
52	Fire of adjacent flammable material from case temperatures due to thermal runaway reaction
53	Failure of electronic protection features resulting in overheating and/or fire (must be in presence of another failure)
54	Incompatible battery charger causes overheating and/or fire
55	Defective battery charger causes overheating and/or fire
56	Battery punctured through case wall causing thermal runaway
57	Crushing/impingement causing potential short between cell electrodes leads to thermal runaway
58	Dropping of battery cell causing potential short between cell electrodes (latent defect) leads to thermal runaway
59	Dropping of battery causing short between cell electrodes leading to thermal runaway
60	Excessive vibration of battery cell causing short between cell electrodes (latent defect) leads to thermal runaway
61	Direct contact of a single battery cell with multiple battery cells results in cell-to-cell external short circuiting leading to thermal runaway
62	Gradual pressure buildup within cell housing due to a latent defect causes thermal runaway
63	Gradual pressure buildup within cell housing due to high temperature conditions leads to thermal runaway
64	Swelling within cell pouch of a LiPo battery due to high temperature conditions leads to thermal runaway
65	Propagation of overheating in a nearby battery leads to thermal runaway
66	Failure of component battery installed in/attached to leads to thermal runaway
67	External short circuit across terminals of battery leads to thermal runaway
68	Malfunction due to faulty battery design leads to thermal runaway
69	Failure of electronic protection features result in thermal runaway (must be in presence of another failure)
70	Incompatible battery charger leads to thermal runaway
71	Defective battery charger leads to thermal runaway
72	Cathode material decomposition leads to thermal runaway
73	Binder chemical reaction with cathode material leads to thermal runaway
74	Cathode reaction with carbon or carbon monoxide leads to thermal runaway
75	Cathode reaction with aluminum leads to thermal runaway

PHL ID	Title
76	Anode passivation dissolution leads to thermal runaway
77	Salt/solvent reaction leads to thermal runaway
78	Heat transfer from one cell runaway in a dense pack with inadequate insulation leads to thermal runaway
79	External heat source leads to thermal runaway
80	Short circuit leads to thermal runaway
81	Anode reaction with electrolyte leads to thermal runaway
82	Anode reaction with binder leads to thermal runaway
83	Separator melting, damaged or defective leads to thermal runaway
84	Over voltage overcharge leads to thermal runaway
85	Overcurrent, overcharge leads to thermal runaway
86	Discharging at an excessive current (external short circuit) leads to thermal runaway
87	Charging the battery outside an acceptable temperature range leads to thermal runaway
88	Over-discharge leads to thermal runaway
89	Failure of imbalance protection for multi-series battery packs leads to thermal runaway
90	Latent damage from repeated discharging to 0V leads to thermal runaway
91	Cell reversal (forced over-discharge) leads to thermal runaway
92	Use in environments for which the battery was not designed leads to thermal runaway
93	Foreign Object Debris (FOD) in battery causes short circuit and leads to thermal runaway
94	Overcharge causes electrical failure of nearby components
95	Over-discharge causes electrical failure of nearby components
96	Malfunction due to faulty battery design causes electrical failure of nearby components
97	Electrical exposure of personnel or equipment (for high current or high voltage applications) results in electrocution
98	Short circuit or damage of adjacent electronics from rapid battery disassembly (explosion/ energetic rupture) due to thermal runaway reaction
99	Short circuit or damage of adjacent electronics from electrolyte leakage due to thermal runaway reaction
100	Failure of electronic protection features (must be in presence of another failure)
101	Incompatible battery charger causes electrical failure of nearby components
102	Defective battery charger causes electrical failure of nearby components
103	Physical burns from case temperatures due to thermal runaway reaction
104	Exposure of damaged battery cell to moisture causes electrolyte decomposition into HF causing burns or deep tissue damage

6.2 PRELIMINARY HAZARD ANALYSIS

Using the assets, failure modes and failure effects identified in the PHL, each hazard was evaluated separately, pairing the failure modes and effects with each asset, and identifying the severity and likelihood of each. The preliminary hazard analysis (PHA) followed the hazard analysis process flow shown in Figure 12. The results of this PHA were used to develop appropriate hazard mitigations, which are part of the basis for the team's recommended methods to achieve safe transport. As shown in the figure, the steps followed included: 1) scoping the analysis; 2) identifying assets (targets) to be protected, including personnel, facilities, the public, the environment, and the devices themselves; 3) identifying hazards associated with each asset, again noting the source, mechanism, and outcome of each hazard; 4) assessing the risk (consequence and likelihood) associated with each hazard; 5) and 6) identifying and evaluating potential mitigations (countermeasures) to reduce risk; and 7) documenting the team's findings.

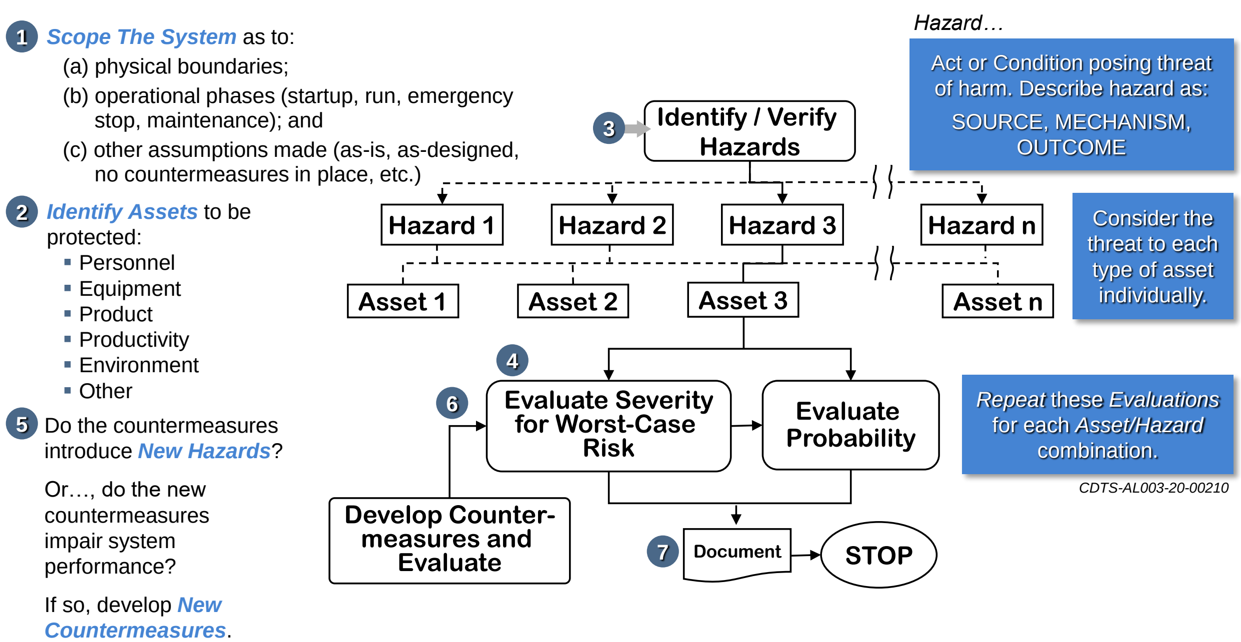

Figure 12: Hazard Identification and Analysis Process

Using the results of the PHL, the PHA is organized by identified failure modes, specifically

1.0 Battery Cell Electrolyte Leakage
2.0 Outgassing
3.0 Explosion/Fragmentation
4.0 Fire/Heat
5.0 Thermal Runaway
6.0 Electrical Failure
7.0 Health Hazard

The tables are structured with a hazard number and description in the first column. The second column identifies the affected targets. These may include personnel (P), equipment (E), mission (M), facilities (F), general public (G), and environment (V).

Columns 3 through 5 present the initial assessed risk, before mitigations. Since the definitions for severity, probability, and Risk Assessment Code (RAC) are tailorable, Figure 13 shows the values and levels that the team used. These definitions are currently used by the FAA and programs within the Department of Defense (DoD), so there is precedent for establishing these risk levels.

Column 6, labeled "Mitigations/Countermeasures" shows recommended controls, ameliorations, and mitigations for each hazard. Each mitigation/countermeasure is identified as either a design (D), engineered safety feature (E), safety device (S), warning device (W), or procedures/training (P/T) consideration, listed in order here by decreasing effectiveness. Procedures and training were combined since each is dependent upon human activity as a control and is more effective when accompanied by the other.

Columns 7 through 9 present the assessed risk after implementation of the recommended mitigations/countermeasures.

The last column, labeled "Verification" identifies the recommended method by which the identified mitigations and countermeasures can be verified as implemented and effective. There are only four acceptable methods by which controls can be verified: through testing (T), demonstration (D), inspection (I), or analysis (A).

Severity of Consequences					
Category/ Descriptive Word	Personnel Illness/ Injury	Equipment Loss ($) **	Down Time	Product Loss	Environmental Effect
1 Catastrophic	Death or permanent total disability	> 10M	> 4 months	Values as for Equipment Loss	Long-term (5 yrs or greater) environmental damage or requiring >$10M to correct and/or in Penalties
2 Critical	Severe injury or severe occupational illness	1M to 10M	2 weeks to 4 months		Medium-term (1-5 yrs) environmental damage or requiring $10M-10M to correct and/or in Penalties
3 Marginal	Minor injury or minor occupational illness	100k to 1M	1 day to 2 weeks		Short-term (<1 yr) environmental damage or requiring$100k-$1M to correct and/or in penalties
4 Negligible	No injury or illness	< 100k	< 1 day		Minor environmental damage, readily repaired and/or requiring < $100k to correct and/or in penalties

Probability of Mishap**		
Level	Descriptive Word	Definition
A	Frequent	Likely to occur often in system life cycle
B	Probable	Will occur several times in system life cycle
C	Occasional	Likely to occur sometime in system life cycle
D	Remote	Not likely to occur in system life cycle, but possible
E	Improbable	So unlikely it can be assumed occurrence may not be experienced
F	Eliminated	Incapable of occurrence

** Life Cycle is assumed to be 30 years or the project life, if shorter

RISK ASSESSMENT MATRIX				
SEVERITY / PROBABILITY	Catastrophic (1)	Critical (2)	Marginal (3)	Negligible (4)
Frequent (A)	High	High	Serious	Medium
Probable (B)	High	High	Serious	Medium
Occasional (C)	High	Serious	Medium	Low
Remote (D)	Serious	Medium	Medium	Low
Improbable (E)	Medium	Medium	Medium	Low
Eliminated (F)	Eliminated			

Figure 13: Hazard Risk Assessment Definitions

Definitions

For the purposes of this PHA, the team used generic terms for specific physical features of a typical battery cell, so the term "Battery Cell Enclosure" is used when referring to the source of electrolyte leakage, rupture or where physical damage is inflicted.

Assumptions/Guidelines

Following is the list of assumptions and guidelines the team used in preparation and development of the PHA:

1. All directives and precautions in 49 CFR § 173.185 that pertain to battery design are assumed to be observed.
2. The transportation condition of a defective or damaged lithium ion battery, including its packaging and storage conditions, cannot be known at the time of this analysis. So, worst case assumption for this analysis is that the battery will not be in any protective enclosure (e.g., original manufacturer's packaging).
3. Unless considered out-of-the-ordinary, mitigations associated with battery design are not included in the list of mitigations.
4. The mitigations and countermeasures listed are primarily associated with actions to be taken when a defective or damaged Li-ion battery is encountered during transportation, not mitigations taken by the manufacturer to prevent a Li-ion battery from becoming damaged and defective.
5. The hazards and mitigations listed are intended to cover all transportation modes (passenger air, cargo air, over-the-road, rail, and above-surface marine). Any causes, hazards or mitigations unique to a specific transportation mode are noted.
6. Unless otherwise noted, it is assumed that a Li-ion battery is thought to be healthy and adequately functional at the beginning of the transportation phase.

<table>
<tr><td colspan="6">Title: Battery Cell Electrolyte Leakage</td><td colspan="5">Revision: Initial</td></tr>
<tr><td>Probability Interval:
Battery Life</td><td>Date:
12 Jun 2019</td><td rowspan="3">Affected Target</td><td colspan="3">Risk Before Mitigations</td><td rowspan="2">Mitigations/Countermeasures
D = Design
E = Engineered Safety Feature
S = Safety Device
W = Warning Device
P/T = Procedures/Training</td><td colspan="3">Risk After Mitigations</td><td rowspan="3">Verification
T=Test
D=Demonstration
I = Inspection
A=Analysis</td></tr>
<tr><td>System:
Li-ion Battery</td><td>Subsystem:
N/A</td><td rowspan="2">Severity</td><td rowspan="2">Probability</td><td rowspan="2">RAC</td><td rowspan="2">Severity</td><td rowspan="2">Probability</td><td rowspan="2">RAC</td></tr>
<tr><td colspan="2">Hazard Number/Description</td><td></td></tr>
<tr><td colspan="2">1.1 Battery cell enclosure is punctured causing electrolyte leakage which results in a chemical exposure</td><td>P
G
E
F
V</td><td>3</td><td>C</td><td>M</td><td>[S] - Provide a containment device adequate to contain any leaks, out-gassing, fire, and fragmentation. The containment device should also protect the battery cells from possible external energy stimulus that can potentially react with electrolyte.

[S/P/T] –Personnel Protection Equipment (PPE) used by personnel to perform containment of damaged and/or defective battery cells.

[P/T] – Training curriculum provided on how to identify the proper PPE and equipment to be used to perform containment of damaged and/or defective battery cells.

[P/T] – Training curriculum provided to inform personnel on the procedures and proper use of equipment for containment of damaged and/or defective battery cells.</td><td>3</td><td>E</td><td>M</td><td>T</td></tr>
<tr><td colspan="2">1.2 Direct contact of a single battery cell with multiple battery cells results in cell-to-cell external short circuiting, battery damage, and electrolyte leakage</td><td>P
G
E
F
V</td><td>3</td><td>C</td><td>M</td><td>All mitigations from 1.1

[E] – Provide a containment device which includes means of isolation between battery cells to reduce likelihood of physical contact between cell units.</td><td>3</td><td>E</td><td>M</td><td>T</td></tr>
<tr><td colspan="2">1.3 Direct contact of a single battery cell with an external short circuit across the terminals of the battery results in battery damage, and electrolyte leakage</td><td>P
G
E
F
V</td><td>3</td><td>C</td><td>M</td><td>All mitigations from 1.1

[E] – Provide a containment device which includes means of isolation between battery cells to reduce likelihood of physical contact between cell units.</td><td>3</td><td>E</td><td>M</td><td>T</td></tr>
</table>

Title: Battery Cell Electrolyte Leakage

Revision: Initial

Probability Interval: Battery Life | **Date:** 12 Jun 2019

System: Li-ion Battery | **Subsystem:** N/A

Hazard Number/Description	Affected Target	Risk Before Mitigations: Severity	Risk Before Mitigations: Probability	Risk Before Mitigations: RAC	Mitigations/Countermeasures (D = Design; E = Engineered Safety Feature; S = Safety Device; W = Warning Device; P/T = Procedures/Training)	Risk After Mitigations: Severity	Risk After Mitigations: Probability	Risk After Mitigations: RAC	Verification (T=Test; D=Demonstration; I = Inspection; A=Analysis)
1.4 Gradual pressure buildup occurs within the cell enclosure caused by a latent defect, resulting in rupture of battery cell.	P G E F V	2 2	D D	M M	All mitigations from 1.1 [P/T] - Provide inspection criteria for battery cells to screen for signs of potential hazards such as aging, electronic protection failures, etc. *(May not apply to passenger air)*	2 2	E E	M M	T I
1.5 Gradual pressure buildup occurs with the cell enclosure caused by faulty battery design, results in rupture of battery cell.	P G E F V	2 2	D D	M M	All mitigations from 1.1 [P/T] - Provide inspection criteria of battery cells to screen for signs of potential hazards such as aging, electronic protection failures, etc. *(May not apply to passenger air)*	2 2	E E	M M	T I
1.6 Gradual pressure buildup occurs with the cell enclosure caused by exposure to high temperature results in rupture of battery cell.	P G E F V	2 2	D D	M M	All mitigations from 1.1 [P/T] - Provide inspection criteria of battery cells to screen for signs of potential hazards such as aging, electronic protection failures, etc. *(May not apply to passenger air)*	2 2	E E	M M	T I
1.7 Gradual pressure buildup occurs with the cell enclosure caused by battery aging results in rupture of battery cell.	P G E F V	2 2	D D	M M	All mitigations from 1.1 [P/T] - Provide inspection criteria of battery cells to screen for signs of potential hazards such as aging, electronic protection failures, etc. *(May not apply to passenger air)*	2 2	E E	M M	T I
1.8 Failure of the equipment that the battery is installed in/attached to leading to electrolyte leakage resulting in a chemical exposure	P G E F V	3	C	M	All mitigations from 1.1	3	E	M	T

Title: Battery Cell Electrolyte Leakage						**Revision:** Initial				
Probability Interval: Battery Life / **Date:** 12 Jun 2019 **System:** Li-ion Battery / **Subsystem:** N/A **Hazard Number/Description**	**Affected Target**	**Risk Before Mitigations** Severity	Probability	RAC	**Mitigations/Countermeasures** D = Design; E = Engineered Safety Feature; S = Safety Device; W = Warning Device; P/T = Procedures/Training	**Risk After Mitigations** Severity	Probability	RAC	**Verification** T=Test D=Demonstration I = Inspection A=Analysis
1.9 Exposure of a damaged battery cell to moisture causes leakage of decomposed electrolyte into Hydrogen Fluoride (HF) resulting in chemical burns and inhalation hazards NOTE: This failure must occur in conjunction with another failure that causes cell enclosure rupture for the hazard to occur	P G E F V	1	C	H	All mitigations from 1.1	1	E	M	T
		1	C	H	[P/T] - Provide instructions that include detailed steps that specify that protection to damaged battery cells is required to prevent exposure to moisture. Caution statement should be identified as part of instructions to alert personnel that failure to provide protection to damaged battery cells may result in a chemical exposure created by electrolyte by-products discharge.	1	D	S	I
1.10 Use of an incompatible battery charger causes battery cell to rupture and leak electrolyte from the battery cell enclosure resulting in a chemical exposure.	P G E F V	3	C	M	[P/T] – Procedures for charging battery cells should identify the battery chargers or include a list of compatible alternative battery chargers that are approved for charging specific batteries.	3	D	M	I
		3	C	M	[P/T] – Prohibit charging of battery cells during transport	3	D	M	I
1.11 Use of a defective battery charger causes battery cell to rupture and leak electrolyte from the battery cell enclosure resulting in a chemical exposure.	P G E F V	3	C	M	[P/T] – Procedures should include steps that specify that personnel verify the operation of battery chargers and inspect the general condition of battery chargers (e.g., aging, use of built in test features on charger to check for latent defects, etc.) before utilizing the equipment to charge battery cells.	3	D	M	I
		3	C	M	[P/T] – Prohibit charging of battery cells during transport	3	D	M	I

Title: Battery Cell Electrolyte Leakage						**Revision:** Initial				
Probability Interval: Battery Life	**Date:** 12 Jun 2019	**Affected Target**	**Risk Before Mitigations**			**Mitigations/Countermeasures**	**Risk After Mitigations**			**Verification**
System: Li-ion Battery	**Subsystem:** N/A									
Hazard Number/Description			Severity	Probability	RAC	D = Design E = Engineered Safety Feature S = Safety Device W = Warning Device P/T = Procedures/Training	Severity	Probability	RAC	T=Test D=Demonstration I = Inspection A=Analysis
1.12 Electronic protection features of battery packs fail to operate causing rupture of one or more battery cells, resulting in electrolyte leakage. NOTE: This failure must occur in conjunction with another failure causing a challenge to the system for the hazard to occur		P G E F V	3	C	M	All mitigations from 1.1	3	E	M	T
1.13 A thermal runaway reaction causes rupture of the battery cell enclosure resulting in electrolyte leakage		P G E F V	3	C	M	All mitigations from 1.1	3	E	M	T

Prepared By/Date:	**Revised By/Date:**	**Target Codes:**	**Approved By/Date:**
J. Teter / R. Dittmar 12 June 2019	J. Delmonte 25 June 2019	P = Personnel M = Mission G = General Public E = Equipment F = Facilities V = Environment	J. Rufe 5 July 2019

<table>
<tr><td colspan="2">Title: Out-Gassing</td><td colspan="10">Revision: Initial</td></tr>
<tr><td>Probability Interval:
Battery Life</td><td>Date:
12 Jun 2019</td><td rowspan="3">Affected Target</td><td colspan="3">Risk Before Mitigations</td><td>Mitigations/Countermeasures</td><td colspan="3">Risk After Mitigations</td><td rowspan="3">Verification
T=Test
D=Demonstration
I = Inspection
A=Analysis</td></tr>
<tr><td>System:
Li-ion Battery</td><td>Subsystem:
N/A</td><td rowspan="2">Severity</td><td rowspan="2">Probability</td><td rowspan="2">RAC</td><td rowspan="2">D = Design
E = Engineered Safety Feature
S = Safety Device
W = Warning Device
P/T = Procedures/Training</td><td rowspan="2">Severity</td><td rowspan="2">Probability</td><td rowspan="2">RAC</td></tr>
<tr><td colspan="2">Hazard Number/Description</td></tr>
<tr><td colspan="2">2.1 A battery cell is inadvertently punctured through the cell enclosure which may cause overtemperature and result in out-gassing</td><td>P
G
E</td><td>3</td><td>C</td><td>M</td><td>[S] - Provide a containment device adequate to contain any leaks, out-gassing, fire, and fragmentation. The containment device should also protect the battery cells from possible external energy stimulus that can potentially react with electrolyte.

[S/P/T] – Personnel Protection Equipment (PPE) used by personnel to perform containment of damaged and/or defective battery cells.

[P/T] – Training curriculum provided on how to identify the proper PPE and equipment to be used to perform containment of damaged and/or defective battery cells.

[P/T] – Training curriculum provided to inform personnel on the procedures and proper use of equipment for containment of damaged and/or defective battery cells.</td><td>3</td><td>E</td><td>M</td><td>T</td></tr>
<tr><td colspan="2">2.2 Battery cell crushing/ impingement occurs causing potential shorts between the cell electrodes and damage to the cell enclosure resulting in out-gassing.</td><td>P
G
E</td><td>3</td><td>C</td><td>M</td><td>All mitigations from 2.1</td><td>3</td><td>E</td><td>M</td><td>T</td></tr>
</table>

Title: Out-Gassing						**Revision:** Initial				
Probability Interval: Battery Life / **Date:** 12 Jun 2019 / **System:** Li-ion Battery / **Subsystem:** N/A	**Affected Target**	**Risk Before Mitigations**			**Mitigations/Countermeasures**	**Risk After Mitigations**			**Verification**
Hazard Number/Description		Severity	Probability	RAC	D = Design; E = Engineered Safety Feature; S = Safety Device; W = Warning Device; P/T = Procedures/Training	Severity	Probability	RAC	T=Test D=Demonstration I = Inspection A=Analysis
2.3 A battery cell with known latent defect(s) is inadvertently dropped causing a potential short between cell electrodes resulting in out-gassing. (Applies to highway, rail or water transport only)	P G E	3	C	M	All mitigations from 2.1	3	E	M	T
		3	C	M	[P/T] – Procedures should include steps that account for OEM recommended handling techniques and protocols to be followed for damaged and/or defective battery cells to ensure that batteries are handled with care and appropriate precautions are observed.	3	D	M	I
		3	C	M	[P/T] – All precautions from 49 CFR 173.185(f), including placement of each cell or battery in individual, non-metallic inner packaging that completely encloses the cell or battery, the use of surrounding cushioning material that is non-combustible, non-conductive, and absorbent, each inner packaging individually placed in an outer packaging that meets the applicable requirements of part 178, subparts L, M, P and Q at the Packing Group I level, and marking of the outer package with “Damaged/ defective lithium ion battery,” as appropriate.	3	E	M	I
2.4 A battery cell is inadvertently dropped causing a potential short between cell electrodes and damage to the cell enclosure resulting in out-gassing.	P G E	3	C	M	All mitigations from 2.1	3	E	M	T
		3	C	M	[P/T] – Procedures should include steps that account for OEM recommended handling techniques and protocols to be followed for damaged and/or defective battery cells to ensure that batteries are handled with care and appropriate precautions are observed.	3	D	M	I

Title: Out-Gassing						**Revision:** Initial				
Probability Interval: Battery Life **Date:** 12 Jun 2019 **System:** Li-ion Battery **Subsystem:** N/A **Hazard Number/Description**	**Affected Target**	**Risk Before Mitigations** Severity	Probability	RAC	**Mitigations/Countermeasures** D = Design E = Engineered Safety Feature S = Safety Device W = Warning Device P/T = Procedures/Training	**Risk After Mitigations** Severity	Probability	RAC	**Verification** T=Test D=Demonstration I = Inspection A=Analysis	
2.5 Battery cell is exposed to water creating a short condition that results in out-gassing from the cell enclosure.	P G E	3 3	C C	M M	All mitigations from 2.1 [P/T] - Provide instructions that include detailed steps that specify that protection to damaged battery cells is required to prevent exposure to moisture. Caution statement should be identified as part of instructions to alert personnel that failure to provide protection to damaged battery cells may result in a chemical exposure created by electrolyte by-products discharge	3 3	E D	M M	T I	
2.6 Exposure of a damaged battery cell to moisture causes electrolyte decomposition into Hydrogen Fluoride (HF) resulting in out-gassing from the cell enclosure.	P G E F V	1 1	C C	H H	All mitigations from 2.1 [P/T] - Provide instructions that include detailed steps that specify that protection to damaged battery cells is required to prevent exposure to moisture. Caution statement should be identified as part of instructions to alert personnel that failure to provide protection to damaged battery cells may result in a chemical exposure created by electrolyte by-products discharge	1 1	E D	M S	T I	
2.7 Electronic protection features of battery packs fail to operate causing damage to one or more battery cells resulting in outgassing NOTE: This failure must occur in conjunction with another failure causing a challenge to the system for the hazard to occur	P G E	3	C	M	All mitigations from 2.1	3	E	M	T	

Title: Out-Gassing

Revision: Initial

Probability Interval: Battery Life / Date: 12 Jun 2019 / System: Li-ion Battery / Subsystem: N/A / Hazard Number/Description	Affected Target	Risk Before Mitigations: Severity	Risk Before Mitigations: Probability	Risk Before Mitigations: RAC	Mitigations/Countermeasures (D = Design; E = Engineered Safety Feature; S = Safety Device; W = Warning Device; P/T = Procedures/Training)	Risk After Mitigations: Severity	Risk After Mitigations: Probability	Risk After Mitigations: RAC	Verification (T=Test, D=Demonstration, I = Inspection, A=Analysis)
2.8 Use of an incompatible battery charger causes damage to battery cell resulting in out-gassing	P G E	3	C	M	[P/T] – Procedures for charging battery cells should identify the battery chargers or include a list of compatible alternative battery chargers that are approved for charging specific batteries.	3	D	M	I
		3	C	M	[P/T] – Prohibit charging of battery cells during transport	3	D	M	I
2.9 Use of a defective battery charger causes damage to battery cell resulting in out-gassing	P G E	3	C	M	[P/T] – Procedures for charging battery cells should identify the battery chargers or include a list of compatible alternative battery chargers that are approved for charging specific batteries.	3	D	M	I
		3	C	M	[P/T] – Prohibit charging of battery cells during transport	3	D	M	I
2.10 Vented gases from a damaged battery cell are released and subsequently ignites NOTE: This failure must occur in conjunction with another failure causing a challenge to the system for the hazard to occur	P G E F V	1	D	S	All mitigations from 2.1 [P/T] - Procedures should include steps that specify the means to extinguish or dilute vented gases from damaged or defective battery cells [P/T] – Develop training curriculum to brief personnel on the procedures for extinguishing fire or diluting the vented gases discharged from damaged and/or defective battery cells	1	E	M	T
2.11 A thermal runaway reaction causes rupture of the battery cell enclosure resulting in out-gassing/gas emission of electrolyte by-products	P G E F V	3	C	M	All mitigations from 2.1	3	E	M	T

Prepared By/Date:	Revised By/Date:	Target Codes:	Approved By/Date:
J. Teter / R. Dittmar 12 June 2019	J. Delmonte 25 June 2019	P = Personnel, E = Equipment M = Mission, F = Facilities G = General Public, V = Environment	J. Rufe 5 July 2019

Title: Explosion/Fragmentation							**Revision:** Initial				
Probability Interval: Battery Life	**Date:** 12 Jun 2019	**Affected Target**	**Risk Before Mitigations**				**Mitigations/Countermeasures**	**Risk After Mitigations**			**Verification**
System: Li-ion Battery	**Subsystem:** N/A										
Hazard Number/Description			Severity	Probability	RAC		D = Design E = Engineered Safety Feature S = Safety Device W = Warning Device P/T = Procedures/Training	Severity	Probability	RAC	T=Test D=Demonstration I = Inspection A=Analysis
3.1 Direct contact of a single battery cell with adjacent battery cells causes cell-to-cell external short circuiting, which may result in explosion and fragmentation		P G E F V	2	C	S		[S] - Provide a containment device adequate to contain any leaks, out-gassing, fire, and fragmentation. The containment device should also protect the battery cells from possible external energy stimulus that can potentially react with electrolyte. [S/P/T] – Personnel Protection Equipment (PPE) used by personnel to perform containment of damaged and/or defective battery cells. [P/T] – Training curriculum provided on how to identify the proper PPE and equipment to be used to perform containment of damaged and/or defective battery cells. [P/T] – Training curriculum provided to inform personnel on the procedures and proper use of equipment for containment of damaged and/or defective battery cells.	2	E	M	T

Title: Explosion/Fragmentation							**Revision:** Initial				
Probability Interval: Battery Life	**Date:** 12 Jun 2019	**Affected Target**	**Risk Before Mitigations**				**Mitigations/Countermeasures**	**Risk After Mitigations**			**Verification**
System: Li-ion Battery	**Subsystem:** N/A		Severity	Probability	RAC		D = Design E = Engineered Safety Feature S = Safety Device W = Warning Device P/T = Procedures/Training	Severity	Probability	RAC	T=Test D=Demonstration I = Inspection A=Analysis
Hazard Number/Description											
3.2 Gradual pressure buildup occurs with the cell housing due to a latent defect, causing rupture which may result in explosion, and fragmentation.		P G E F V	2 2 2	D D D	M M M		All mitigations from 3.1 [P/T] - Provide inspection criteria of battery cells to screen for signs of potential hazards such as aging, electronic protection failures, etc. [P/T] – All precautions from 49 CFR 173.185(f), including placement of each cell or battery in individual, non-metallic inner packaging that completely encloses the cell or battery, the use of surrounding cushioning material that is non-combustible, non-conductive, and absorbent, each inner packaging individually placed in an outer packaging that meets the applicable requirements of part 178, subparts L, M, P and Q at the Packing Group I level, and marking of the outer package with “Damaged/ defective lithium ion battery,” as appropriate.	2 2 2	E E E	M M M	T I I
3.3 Gradual pressure buildup occurs within the cell enclosure due to faulty battery design, causing rupture of battery cell which may result in explosion and fragmentation.		P G E F V	2 2	D D	M M		All mitigations from 3.1 [P/T] - Provide inspection criteria of battery cells to screen for signs of potential hazards such as aging, electronic protection failures, etc.	2 2	E E	M M	T I
3.4 Gradual pressure buildup occurs within the cell enclosure due to battery aging, causing rupture of battery cell which may result in explosion and fragmentation.		P G E F V	2 2	D D	M M		All mitigations from 3.1 [P/T] - Provide inspection criteria of battery cells to screen for signs of potential hazards such as aging, electronic protection failures, etc.	2 2	E E	M M	T I

Title: Explosion/Fragmentation		**Revision:** Initial								
Probability Interval: Battery Life **System:** Li-ion Battery **Hazard Number/Description**	**Date:** 12 Jun 2019 **Subsystem:** N/A	**Affected Target**	**Risk Before Mitigations** Severity	Probability	RAC	**Mitigations/Countermeasures** D = Design E = Engineered Safety Feature S = Safety Device W = Warning Device P/T = Procedures/Training	**Risk After Mitigations** Severity	Probability	RAC	**Verification** T=Test D=Demonstration I = Inspection A=Analysis
3.5 Gradual pressure buildup occurs within the cell enclosure due to exposure to high temperature, causing rupture of battery cell which may result in explosion and fragmentation.		P G E F V	2 2	D D	M M	All mitigations from 3.1 [P/T] - Provide inspection criteria of battery cells to screen for signs of potential hazards such as aging, electronic protection failures, etc.	2 2	E E	M M	T I
3.6 Battery cell crushing/impingement occurs causing potential shorts between the cell electrodes resulting in cell enclosure pressure buildup and subsequent explosion and fragmentation.		P G E F V	2	C	S	All mitigations from 3.1	2	E	M	T
3.7 A battery cell is inadvertently punctured through the cell enclosure causing overtemperature and leading to explosion and fragmentation		P G E F V	2	C	S	All mitigations from 3.1	2	E	M	T
3.8 Failure of the equipment that the battery is installed in/attached to causes damage to battery cell resulting in explosion and fragmentation.		P G E F V	2	C	S	All mitigations from 3.1	2	E	M	T
3.9 Electronic protection features of battery packs fail to operate causing damage to one or more battery cells resulting in explosion and fragmentation NOTE: This failure must occur in conjunction with another failure causing a challenge to the system for the hazard to occur		P G E F V	2 2	D D	M M	All mitigations from 3.1 [P/T] - Provide inspection criteria of battery cells to screen for signs of potential hazards such as aging, electronic protection failures, etc.	2 2	E E	M M	T I

Title: Explosion/Fragmentation						**Revision:** Initial				
Probability Interval: Battery Life; **Date:** 12 Jun 2019; **System:** Li-ion Battery; **Subsystem:** N/A; **Hazard Number/Description**	**Affected Target**	**Risk Before Mitigations** Severity	Probability	RAC	**Mitigations/Countermeasures** D = Design; E = Engineered Safety Feature; S = Safety Device; W = Warning Device; P/T = Procedures/Training	**Risk After Mitigations** Severity	Probability	RAC	**Verification** T=Test D=Demonstration I = Inspection A=Analysis
3.10 Use of an incompatible battery charger causes damage to battery cell resulting in explosion and fragmentation	P G E F V	2	C	S	[P/T] – Procedures for charging battery cells should identify the battery chargers or include a list of compatible alternative battery chargers that are approved for charging specific batteries	2	D	M	I
		2	C	S	[P/T] – Prohibit charging of battery cells during transport	2	D	M	I
3.11 Use of a defective battery charger causes damage to battery cell resulting in explosion and fragmentation	P G E F V	2	C	S	[P/T] – Procedures for charging battery cells should identify the battery chargers or include a list of compatible alternative battery chargers that are approved for charging specific batteries	2	D	M	I
		2	C	S	[P/T] – Prohibit charging of battery cells during transport	2	D	M	I
3.12 Propagation of an event from one battery cell to another occurs resulting in explosion and fragmentation	P G E F V	1	D	S	All mitigations from 3.1	1	E	M	T
		1	D	S	[E] Develop criteria, methods, and techniques to maintain separation and isolation between multiple battery cells to reduce likelihood of propagation of an event in one cell to an adjacent battery cell	1	E	M	T
		1	D	S	[P/T] Procedures should include detailed steps to inspect for adequate separation and isolation between multiple battery cells to reduce likelihood of propagation of battery cell failure event	1	E	M	D
3.13 An external short occurs across the terminals of the battery packs resulting in explosion and fragmentation	P G E F V	2	C	S	All mitigations from 3.1	2	E	M	T
Prepared By/Date: J. Teter / R. Dittmar	**Revised By/Date:** J. Delmonte				**Target Codes:** P = Personnel, E = Equipment, M = Mission, F = Facilities	**Approved By/Date:** J. Rufe			

Title: Explosion/Fragmentation							**Revision:** Initial				
Probability Interval: Battery Life	**Date:** 12 Jun 2019	**Affected Target**	**Risk Before Mitigations**			**Mitigations/Countermeasures**		**Risk After Mitigations**			**Verification**
System: Li-ion Battery	**Subsystem:** N/A		Severity	Probability	RAC	D = Design E = Engineered Safety Feature S = Safety Device	W = Warning Device P/T = Procedures/Training	Severity	Probability	RAC	T=Test D=Demonstration I = Inspection A=Analysis
Hazard Number/Description											

12 June 2019	25 June 2019	G = General Public V = Environment	5 July 2019

Title: Fire/Heat							**Revision:** Initial				
Probability Interval: Battery Life	**Date:** 12 Jun 2019	**Affected Target**	**Risk Before Mitigations**			**Mitigations/Countermeasures**	**Risk After Mitigations**			**Verification**	
System: Li-ion Battery	**Subsystem:** N/A										
Hazard Number/Description			Severity	Probability	RAC	D = Design E = Engineered Safety Feature S = Safety Device W = Warning Device P/T = Procedures/Training	Severity	Probability	RAC	T=Test D=Demonstration I = Inspection A=Analysis	
4.1 Direct contact of a single battery cell with adjacent battery cells, causing cell-to-cell external short circuiting, may result in cell enclosure rupture followed by venting with flame.		P G E F V	2	C	S	[S] - Provide a containment device adequate to contain any leaks, out-gassing, fire, and fragmentation. The containment device should also protect the battery cells from possible external energy stimulus that can potentially react with electrolyte. [S/P/T] – Personnel Protection Equipment (PPE) used by personnel to perform containment of damaged and/or defective battery cells. [P/T] – Training curriculum provided on how to identify the proper PPE and equipment to be used to perform containment of damaged and/or defective battery cells. [P/T] – Training curriculum provided to inform personnel on the procedures and proper use of equipment for containment of damaged and/or defective battery cells.	2	E	M	T	

Title: Fire/Heat							**Revision:** Initial				
Probability Interval: Battery Life	**Date:** 12 Jun 2019	**Affected Target**	**Risk Before Mitigations**			**Mitigations/Countermeasures**	**Risk After Mitigations**			**Verification**
System: Li-ion Battery	**Subsystem:** N/A		Severity	Probability	RAC	D = Design E = Engineered Safety Feature S = Safety Device W = Warning Device P/T = Procedures/Training	Severity	Probability	RAC	T=Test D=Demonstration I = Inspection A=Analysis
Hazard Number/Description										
4.2 Gradual pressure buildup occurs within the cell enclosure due to a latent defect, causing rupture of battery cell which may result in venting with flame and a fire		P G E F V	2 2 2	D D D	M M M	All mitigations from 4.1 [P/T] - Provide inspection criteria of battery cells to screen for signs of potential hazards such as aging, electronic protection failures, etc. [P/T] – All precautions from 49 CFR 173.185(f), including placement of each cell or battery in individual, non-metallic inner packaging that completely encloses the cell or battery, the use of surrounding cushioning material that is non-combustible, non-conductive, and absorbent, each inner packaging individually placed in an outer packaging that meets the applicable requirements of part 178, subparts L, M, P and Q at the Packing Group I level, and marking of the outer package with “Damaged/ defective lithium ion battery,” as appropriate.	2 2 2	E E E	M M M	T I I
4.3 Gradual pressure buildup occurs within the cell enclosure due to faulty battery design, causing rupture of battery cell which may result in venting with flame and a fire		P G E F V	2 2	D D	M M	All mitigations from 4.1 [P/T] - Provide inspection criteria of battery cells to screen for signs of potential hazards such as aging, electronic protection failures, etc.	2 2	E E	M M	T I
4.4 Gradual pressure buildup occurs within the cell enclosure due to battery aging, causing rupture of battery cell which may result in venting with flame and a fire		P G E F V	2 2	D D	M M	All mitigations from 4.1 [P/T] - Provide inspection criteria of battery cells to screen for signs of potential hazards such as aging, electronic protection failures, etc.	2 2	E E	M M	T I

Title: Fire/Heat							**Revision:** Initial				
Probability Interval: Battery Life	**Date:** 12 Jun 2019	**Affected Target**	**Risk Before Mitigations**			**Mitigations/Countermeasures**	**Risk After Mitigations**			**Verification**
System: Li-ion Battery	**Subsystem:** N/A		Severity	Probability	RAC	D = Design E = Engineered Safety Feature S = Safety Device W = Warning Device P/T = Procedures/Training	Severity	Probability	RAC	T=Test D=Demonstration I = Inspection A=Analysis
Hazard Number/Description										
4.5 Gradual pressure buildup occurs within the cell enclosure due to exposure to high temperature, causing rupture of battery cell which may result in venting with flame and a fire		P G E F V	2 2	D D	M M	All mitigations from 4.1 [P/T] - Provide inspection criteria of battery cells to screen for signs of potential hazards such as aging, electronic protection failures, etc.	2 2	E E	M M	T I
4.6 Battery cell is exposed to water creating a short condition that may result in a fire		P G E F V	2 2	C C	S S	All mitigations from 4.1 [P/T] - Provide instructions that include detailed steps that specify that protection to damaged battery cells is required to prevent exposure to moisture. Caution statement should be identified as part of instructions to alert personnel that failure to provide protection to damaged battery cells may result in a chemical exposure created by electrolyte by-products discharge.	2 2	E D	M M	T I
4.7 A battery cell is inadvertently punctured through the cell enclosure which may result in overtemperature leading to a fire		P G E F V	2	C	S	All mitigations from 4.1	2	E	M	T
4.8 Failure of the equipment that the battery is installed in/attached to causes damage to battery cell resulting in a fire		P G E F V	2	C	S	All mitigations from 4.1	2	E	M	T

Title: Fire/Heat							**Revision:** Initial				
Probability Interval: Battery Life **System:** Li-ion Battery	**Date:** 12 Jun 2019 **Subsystem:** N/A	**Affected Target**	**Risk Before Mitigations**			**Mitigations/Countermeasures**		**Risk After Mitigations**			**Verification**
Hazard Number/Description			Severity	Probability	RAC	D = Design E = Engineered Safety Feature S = Safety Device	W = Warning Device P/T = Procedures/Training	Severity	Probability	RAC	T=Test D=Demonstration I = Inspection A=Analysis
4.9 Electronic protection features of battery packs fail to operate causing damage to one or more battery cell which may result in a fire NOTE: This failure must occur in conjunction with another failure causing a challenge to the system for the hazard to occur		P G E F V	2 2	D D	M M	All mitigations from 4.1 [P/T] - Provide inspection criteria of battery cells to screen for signs of potential hazards such as aging, electronic protection failures, etc.		2 2	E E	M M	T I
4.10 Use of an incompatible battery charger causes damage to battery cell resulting in overtemperature and a fire		P G E F V	2 2	C C	S S	[P/T] – Procedures for charging battery cells should identify the battery chargers or include a list of compatible alternative battery chargers that are approved for charging specific batteries [P/T] – Prohibit charging of battery cells during transport		2 2	D D	M M	I I
4.11 Use of a defective battery charger causes damage to battery cell resulting in a fire		P G E F V	2 2	C C	S S	[P/T] – Procedures for charging battery cells should identify the battery chargers or include a list of compatible alternative battery chargers that are approved for charging specific batteries [P/T] – Prohibit charging of battery cells during transport		2 2	D D	M M	I I
4.12 Vented gases are released from a damaged battery cell and subsequently ignited, resulting in a fire NOTE: This failure must occur in conjunction with another failure causing a challenge to the system for the hazard to occur		P G E F V	2 2 2	D D D	M M M	All mitigations from 4.1 [P/T] - Procedures should include steps that specify the means to extinguish or dilute vented gases from damaged or defective battery cells [P/T] – Develop training curriculum to brief personnel on the procedures for extinguishing fire or diluting the vented gases discharged from damaged and/or defective battery cells		2 2 2	E E E	M M M	T I I

Title: Fire/Heat						**Revision:** Initial				
Probability Interval: Battery Life / **Date:** 12 Jun 2019 / **System:** Li-ion Battery / **Subsystem:** N/A	**Affected Target**	**Risk Before Mitigations**			**Mitigations/Countermeasures**	**Risk After Mitigations**			**Verification**
Hazard Number/Description		Severity	Probability	RAC	D = Design, E = Engineered Safety Feature, S = Safety Device, W = Warning Device, P/T = Procedures/Training	Severity	Probability	RAC	T=Test, D=Demonstration, I = Inspection, A=Analysis
4.13 Propagation of an event from one battery cell to another results in a fire	P G E F V	1	D	S	All mitigations from 4.1	1	E	M	T
		1	D	S	[E] Develop criteria, methods, and techniques to maintain separation and isolation between multiple battery cells to reduce likelihood of propagation of an event in one cell to an adjacent battery cell	1	E	M	T
		1	D	S	[P/T] Procedures should include detailed steps to inspect for adequate separation and isolation between multiple battery cells to reduce likelihood of propagation of battery cell failure event	1	E	M	D
4.14 A fire of adjacent flammable material occurs due to high battery cell enclosure temperatures from a thermal runaway reaction	P G E F V	2	C	S	All mitigations from 4.1	2	E	M	T
		2	C	S	[E] Utilize packaging that does not contain components that are flammable	2	E	M	D
		2	C	S	[E] Develop criteria, methods, and techniques to maintain separation and isolation between multiple battery cells to reduce likelihood of propagation of an event in one cell to an adjacent battery cell	2	D	M	I
		2	C	S	[P/T] Procedures should include detailed steps to inspect for adequate separation and isolation between multiple battery cells to reduce likelihood of propagation of battery cell failure event	2	D	M	I
4.15 An external short occurs across the terminals of the battery packs resulting in a fire	P G E F V	2	C	S	All mitigations from 4.1	2	E	M	T

Title: Fire/Heat							**Revision:** Initial			
Probability Interval: Battery Life	**Date:** 12 Jun 2019	**Affected Target**	**Risk Before Mitigations**			**Mitigations/Countermeasures**	**Risk After Mitigations**			**Verification**
System: Li-ion Battery	**Subsystem:** N/A									
Hazard Number/Description			Severity	Probability	RAC	D = Design; E = Engineered Safety Feature; S = Safety Device; W = Warning Device; P/T = Procedures/Training	Severity	Probability	RAC	T=Test; D=Demonstration; I = Inspection; A=Analysis
4.16 Battery cells with leaking flammable electrolyte fluid on surface of the cell enclosure are subjected to excessive contact with a conductive surface creating an excessive amount of friction against the battery cell and electrostatic discharge that results in a fire. NOTE: This failure must occur in conjunction with another failure causing a challenge to the system for the hazard to occur		P G E F V	2	D	M	All mitigations from 4.1	2	E	M	T
4.17 Incompatible chemical composition of battery components may cause the cell enclosure to rupture and vent with flame resulting in a fire		P G E F V	2	D	M	All mitigations from 4.1	2	E	M	T
Prepared By/Date: J. Teter / R. Dittmar 12 June 2019	**Revised By/Date:** J. Delmonte 25 June 2019		**Target Codes:** P = Personnel; M = Mission; G = General Public; E = Equipment; F = Facilities; V = Environment				**Approved By/Date:** J. Rufe 5 July 2019			

Title: Thermal Runaway						**Revision:** Initial				
Probability Interval: Battery Life	**Date:** 12 Jun 2019	**Affected Target**	**Risk Before Mitigations**			**Mitigations/Countermeasures**	**Risk After Mitigations**			**Verification**
System: Li-ion Battery	**Subsystem:** N/A									
Hazard Number/Description			Severity	Probability	RAC	D = Design; E = Engineered Safety Feature; S = Safety Device; W = Warning Device; P/T = Procedures/Training	Severity	Probability	RAC	T=Test D=Demonstration I = Inspection A=Analysis
5.1 Direct contact of a single battery cell with adjacent battery cells causes cell-to-cell external short circuiting, may result in cell enclosure rupture followed by venting with flame and a thermal runaway reaction.		P G E F V	2	C	S	[S] - Provide a containment device adequate to contain any leaks, out-gassing, fire, and fragmentation. The containment device should also protect the battery cells from possible external energy stimulus that can potentially react with electrolyte. [S/P/T] – Personnel Protection Equipment (PPE) used by personnel to perform containment of damaged and/or defective battery cells. [P/T] – Training curriculum provided on how to identify the proper PPE and equipment to be used to perform containment of damaged and/or defective battery cells. [P/T] – Training curriculum provided to inform personnel on the procedures and proper use of equipment for containment of damaged and/or defective battery cells.	2	E	M	T

Title: Thermal Runaway							**Revision:** Initial				
Probability Interval: Battery Life	**Date:** 12 Jun 2019	**Affected Target**	**Risk Before Mitigations**				**Mitigations/Countermeasures**	**Risk After Mitigations**			**Verification**
System: Li-ion Battery	**Subsystem:** N/A		Severity	Probability	RAC		D = Design E = Engineered Safety Feature S = Safety Device W = Warning Device P/T = Procedures/Training	Severity	Probability	RAC	T=Test D=Demonstration I = Inspection A=Analysis
Hazard Number/Description											
5.2 Gradual pressure buildup occurs within the cell enclosure due to a latent defect, causing rupture of battery cell which may result in venting with flame and a thermal runaway reaction		P G E F V	2 2 2	D D D	M M M		All mitigations from 5.1 [P/T] - Provide inspection criteria of battery cells to screen for signs of potential hazards such as aging, electronic protection failures, etc. [P/T] – All precautions from 49 CFR 173.185(f), including placement of each cell or battery in individual, non-metallic inner packaging that completely encloses the cell or battery, the use of surrounding cushioning material that is non-combustible, non-conductive, and absorbent, each inner packaging individually placed in an outer packaging that meets the applicable requirements of part 178, subparts L, M, P and Q at the Packing Group I level, and marking of the outer package with “Damaged/ defective lithium ion battery,” as appropriate.	2 2 2	E E E	M M M	T I I
5.3 Gradual pressure buildup occurs within the cell enclosure due to faulty battery design, causing rupture of battery cell which may result in venting with flame and a thermal runaway reaction.		P G E F V	2 2	D D	M M		All mitigations from 5.1 [P/T] - Provide inspection criteria of battery cells to screen for signs of potential hazards such as aging, electronic protection failures, etc.	2 2	E E	M M	T I
5.4 Gradual pressure buildup occurs within the cell enclosure due to battery aging, causing rupture of battery cell which may result in venting with flame and a fire.		P G E F V	2 2	D D	M M		All mitigations from 5.1 [P/T] - Provide inspection criteria of battery cells to screen for signs of potential hazards such as aging, electronic protection failures, etc.	2 2	E E	M M	T I
5.5 Gradual pressure buildup occurs within the cell enclosure due to exposure to high		P G E	2 2	D D	M M		All mitigations from 5.1 [P/T] - Provide inspection criteria of battery cells to screen for signs of potential hazards such as aging,	2 2	E E	M M	T I

Title: Thermal Runaway							**Revision:** Initial				
Probability Interval: Battery Life	**Date:** 12 Jun 2019	**Affected Target**	**Risk Before Mitigations**			**Mitigations/Countermeasures**	**Risk After Mitigations**			**Verification**	
System: Li-ion Battery	**Subsystem:** N/A		Severity	Probability	RAC	D = Design E = Engineered Safety Feature S = Safety Device W = Warning Device P/T = Procedures/Training	Severity	Probability	RAC	T=Test D=Demonstration I = Inspection A=Analysis	
Hazard Number/Description											
temperature, causing rupture of battery cell which may result in venting with flame and a fire		F V				electronic protection failures, etc.					
5.6 Battery cell crushing/ impingement occurs causing potential shorts between the cell electrodes resulting in cell enclosure pressure buildup and the initiation of a thermal runaway reaction		P G E F V	2	C	S	All mitigations from 5.1	2	E	M	T	
5.7 A battery cell is inadvertently punctured through the cell enclosure which may cause overtemperature and result in the initiation of a thermal runaway reaction		P G E F V	2	C	S	All mitigations from 5.1	2	E	M	T	
5.8 Failure of the equipment that the battery is installed in/attached to causes damage to battery cell resulting in the initiation of a thermal runaway reaction		P G E F V	2	C	S	All mitigations from 5.1	2	E	M	T	
5.9 Electronic protection features of battery packs fail to operate causing damage to one or more battery cells which may result in the initiation of a thermal runaway reaction NOTE: This failure must occur in conjunction with another failure causing a challenge to the system for the hazard to occur		P G E F V	2 2	D D	M M	All mitigations from 5.1 [P/T] - Provide inspection criteria of battery cells to screen for signs of potential hazards such as aging, electronic protection failures, etc.	2 2	E E	M M	T I	
5.10 Use of an incompatible battery charger causes damage to battery cell resulting in overtemperature and the initiation of a thermal runaway reaction		P G E F V	2	C	S	[P/T] – Procedures for charging battery cells should identify the battery chargers or include a list of compatible alternative battery chargers that are approved for charging specific batteries	2	D	M	I	

Title: Thermal Runaway										**Revision:** Initial
Probability Interval: Battery Life	**Date:** 12 Jun 2019	**Affected Target**	**Risk Before Mitigations**			**Mitigations/Countermeasures**	**Risk After Mitigations**			**Verification**
System: Li-ion Battery	**Subsystem:** N/A									
Hazard Number/Description			Severity	Probability	RAC	D = Design E = Engineered Safety Feature S = Safety Device W = Warning Device P/T = Procedures/Training	Severity	Probability	RAC	T=Test D=Demonstration I = Inspection A=Analysis
			2	C	S	[P/T] – Prohibit charging of battery cells during transport	2	D	M	I
5.11 Use of a defective battery charger causes damage to battery cell resulting in the initiation of a thermal runaway reaction		P G E F V	2	C	S	[P/T] – Procedures for charging battery cells should identify the battery chargers or include a list of compatible alternative battery chargers that are approved for charging specific batteries	2	D	M	I
			2	C	S	[P/T] – Prohibit charging of battery cells during transport	2	D	M	I
5.12 A battery cell with known latent defect is inadvertently dropped causing a potential short between cell electrodes resulting in a thermal runaway reaction.		P G E F V	2	C	S	All mitigations from 5.1	2	E	M	T
			2	C	S	[P/T] - Provide inspection criteria of battery cells to screen for signs of potential hazards such as aging, electronic protection failures, etc.	2	D	M	I
			2	C	S	[P/T] – All precautions from 49 CFR 173.185(f), including placement of each cell or battery in individual, non-metallic inner packaging that completely encloses the cell or battery, the use of surrounding cushioning material that is non-combustible, non-conductive, and absorbent, each inner packaging individually placed in an outer packaging that meets the applicable requirements of part 178, subparts L, M, P and Q at the Packing Group I level, and marking of the outer package with "Damaged/ defective lithium ion battery," as appropriate.	2	D	M	I

Title: Thermal Runaway					**Revision:** Initial				
Probability Interval: Battery Life; **Date:** 12 Jun 2019; **System:** Li-ion Battery; **Subsystem:** N/A	**Affected Target**	**Risk Before Mitigations**			**Mitigations/Countermeasures**	**Risk After Mitigations**			**Verification**
Hazard Number/Description		Severity	Probability	RAC	D = Design; E = Engineered Safety Feature; S = Safety Device; W = Warning Device; P/T = Procedures/Training	Severity	Probability	RAC	T=Test; D=Demonstration; I = Inspection; A=Analysis
5.13 Propagation of an event from one battery cell to another occurs resulting in a thermal runaway reaction	P G E F V	1	D	S	All mitigations from 5.1	1	E	M	T
		1	D	S	[E] Develop criteria, methods, and techniques to maintain separation and isolation between multiple battery cells to reduce likelihood of propagation of an event in one cell to an adjacent battery cell	1	E	M	T
		1	D	S	[P/T] Procedures should include detailed steps to inspect for adequate separation and isolation between multiple battery cells to reduce likelihood of propagation of battery cell failure event.	1	E	M	D
5.14 The battery cell is subjected to vibration during transport causing a potential short between cell electrodes and resulting in the initiation of a thermal runaway reaction	P G E F V	2	C	S	All mitigations from 5.1	2	E	M	T
		2	C	S	[P/T] - Provide instructions that include detailed steps that specify protection to battery cells from excessive vibration during transport. Caution statement should be identified as part of instructions to alert personnel to handle battery cells with care while packing them into transport containers.	2	D	M	I
5.15 An external short occurs across the terminals of the battery packs results in a thermal runaway	P G E F V	2	C	S	All mitigations from 5.1	2	E	M	T

Title: Thermal Runaway						**Revision:** Initial				
Probability Interval: Battery Life **Date:** 12 Jun 2019 **System:** Li-ion Battery **Subsystem:** N/A	**Affected Target**	**Risk Before Mitigations**			**Mitigations/Countermeasures**		**Risk After Mitigations**			**Verification**
Hazard Number/Description		Severity	Probability	RAC	D = Design E = Engineered Safety Feature S = Safety Device	W = Warning Device P/T = Procedures/Training	Severity	Probability	RAC	T=Test D=Demonstration I = Inspection A=Analysis
5.16 Latent defect (decomposition) in cathode material causes damage to the battery cell resulting in the initiation of a thermal runaway reaction	P G E F V	2	C	S	All mitigations from 5.1		2	E	M	T
		2	C	S	[P/T] - Provide inspection criteria of battery cells to screen for signs of potential hazards such as aging, electronic protection failures, etc.		2	D	M	I
		2	C	S	[P/T] – All precautions from 49 CFR 173.185(f), including placement of each cell or battery in individual, non-metallic inner packaging that completely encloses the cell or battery, the use of surrounding cushioning material that is non-combustible, non-conductive, and absorbent, each inner packaging individually placed in an outer packaging that meets the applicable requirements of part 178, subparts L, M, P and Q at the Packing Group I level, and marking of the outer package with “Damaged/ defective lithium ion battery,” as appropriate.		2	D	M	I
5.17 Latent defect created by a binder chemical reaction with the cathode material causes damage to the battery cell resulting in the initiation of a thermal runaway reaction	P G E F V	2	C	S	All mitigations from 5.16		2	D	M	T/I
5.18 Latent defect created by the cathode material reacting with carbon or carbon monoxide causes damage to the battery cell resulting in a thermal runaway	P G E F V	2	C	S	All mitigations from 5.16		2	D	M	T/I

Title: Thermal Runaway						**Revision:** Initial				
Probability Interval: Battery Life; **Date:** 12 Jun 2019; **System:** Li-ion Battery; **Subsystem:** N/A	**Affected Target**	**Risk Before Mitigations**			**Mitigations/Countermeasures**	**Risk After Mitigations**			**Verification**
Hazard Number/Description		Severity	Probability	RAC	D = Design E = Engineered Safety Feature S = Safety Device W = Warning Device P/T = Procedures/Training	Severity	Probability	RAC	T=Test D=Demonstration I = Inspection A=Analysis
5.19 Latent defect created by the cathode material reacting with aluminum foil coating causes damage to the battery cell resulting in the initiation of a thermal runaway reaction	P G E F V	2	C	S	All mitigations from 5.16	2	D	M	T/I
5.20 Latent defect created by anode passivation dissolution causes damage to the battery cell resulting in the initiation of a thermal runaway reaction	P G E F V	2	C	S	All mitigations from 5.16	2	D	M	T/I
5.21 Latent defect created by salt/solvent reaction causes damage to the battery cell resulting in the initiation of a thermal runaway reaction	P G E F V	2	C	S	All mitigations from 5.16	2	D	M	T/I
5.22 Heat transfer from one battery cell undergoing a thermal runaway reaction located in a dense pack containing inadequate insulation propagates to adjacent battery cells resulting in the initiation of multiple thermal runaway events	P G E F V	1	D	S	All mitigations from 5.1	1	E	M	T
		1	D	S	[E] Develop criteria, methods, and techniques to maintain separation and isolation between multiple battery cells to reduce likelihood of propagation of an event in one cell to an adjacent battery cell	1	E	M	T
		1	D	S	[P/T] Procedures should include detailed steps to inspect for adequate separation and isolation between multiple battery cells to reduce likelihood of propagation of battery cell failure event.	1	E	M	D
5.23 Battery cells are exposed to an external heat source causing damage to the battery cell anode cathode elements resulting in the initiation of a thermal runaway reaction	P G E F V	2	C	S	All mitigations from 5.1	2	E	M	T

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Probability Interval: Battery Life; **Date:** 12 Jun 2019; **System:** Li-ion Battery; **Subsystem:** N/A	**Affected Target**	**Risk Before Mitigations**			**Mitigations/Countermeasures**	**Risk After Mitigations**			**Verification**	
Hazard Number/Description		Severity	Probability	RAC	D = Design; E = Engineered Safety Feature; S = Safety Device; W = Warning Device; P/T = Procedures/Training	Severity	Probability	RAC	T=Test; D=Demonstration; I = Inspection; A=Analysis	
5.24 Latent defect created by the anode reacting with the electrolyte causes internal damage to the battery cell resulting in the initiation of a thermal runaway reaction	P G E F V	2	C	S	All mitigations from 5.16	2	D	M	T/I	
5.25 Latent defect created by the anode reacting with the binder causes internal damage to the battery cell resulting in the initiation of a thermal runaway	P G E F V	2	C	S	All mitigations from 5.16	2	D	M	T/I	
5.26 Battery cells become overheated causing the separator to melt resulting in the initiation of a thermal runaway	P G E F V	2	C	S	All mitigations from 5.1	2	E	M	T	
5.27 Latent defect created by the use of a damaged/defective separator causes damage to the battery cell from overheating resulting in the initiation of a thermal runaway reaction	P G E F V	2	C	S	All mitigations from 5.16	2	D	M	T/I	
5.28 Battery pack assemblies are subjected to overvoltage/overcurrent charging causing damage from overheating resulting in the initiation of a thermal runaway reaction	P G E F V	2	C	S	All mitigations from 5.16	2	D	M	T/I	
		2	C	S	[P/T] – Procedures for charging battery cells should identify the battery chargers or include a list of compatible alternative battery chargers that are approved for charging specific batteries	2	D	M	I	
		2	C	S	[P/T] – Prohibit charging of battery cells during transport	2	D	M	I	

Title: Thermal Runaway						**Revision:** Initial				
Probability Interval: Battery Life **Date:** 12 Jun 2019 **System:** Li-ion Battery **Subsystem:** N/A **Hazard Number/Description**	**Affected Target**	**Risk Before Mitigations** Severity	Probability	RAC	**Mitigations/Countermeasures** D = Design E = Engineered Safety Feature S = Safety Device W = Warning Device P/T = Procedures/Training	**Risk After Mitigations** Severity	Probability	RAC	**Verification** T=Test D=Demonstration I = Inspection A=Analysis
5.29 Discharging of battery pack assemblies at an excessive current (external short circuit) results in the initiation of a thermal runaway reaction	P G E F V	2	C	S	All mitigations from 5.1	2	E	M	T
5.30 Charging of battery pack assemblies outside an acceptable temperature range occurs resulting in the initiation of a thermal runaway	P G E F V	2	C	S	All mitigations from 5.16	2	D	M	T/I
		2	C	S	[P/T] – Procedures for charging battery cells should identify the battery chargers or include a list of compatible alternative battery chargers that are approved for charging specific batteries	2	D	M	I
		2	C	S	[P/T] – Prohibit charging of battery cells during transport	2	D	M	I
5.31 Over discharge of battery pack assemblies' results in the initiation of a thermal runaway reaction	P G E F V	2	C	S	All mitigations from 5.1	2	E	M	T
5.32 Imbalance protection fails for multi-series battery packs causing damage to the battery packs resulting in the initiation of a thermal runaway reaction	P G E F V	2	C	S	All mitigations from 5.1	2	E	M	T
5.33 Latent damage to battery packs from repeated discharging of cells to 0V results in the initiation of a thermal runaway reaction	P G E F V	2	C	S	All mitigations from 5.16	2	D	M	T/I

Title: Thermal Runaway						**Revision:** Initial				
Probability Interval: Battery Life **Date:** 12 Jun 2019 **System:** Li-ion Battery **Subsystem:** N/A	**Affected Target**	**Risk Before Mitigations**			**Mitigations/Countermeasures**	**Risk After Mitigations**			**Verification**	
Hazard Number/Description		Severity	Probability	RAC	D = Design E = Engineered Safety Feature S = Safety Device W = Warning Device P/T = Procedures/Training	Severity	Probability	RAC	T=Test D=Demonstration I = Inspection A=Analysis	
5.34 Cell reversal (forced over-discharge) results in the initiation of a thermal runaway reaction	P G E F V	2	C	S	All mitigations from 5.1	2	E	M	T	
5.35 Use in environments for which the battery was not designed results in the initiation of a thermal runaway reaction	P G E F V	2	C	S	All mitigations from 5.1	2	E	M	T	
5.36 Foreign object contact with the battery results in the initiation of a thermal runaway reaction	P G E F V	2	D	M	All mitigations from 5.1	2	E	M	T	

Prepared By/Date:	**Revised By/Date:**	**Target Codes:**		**Approved By/Date:**
J. Teter / R. Dittmar 12 June 2019	J. Delmonte 25 June 2019	P = Personnel M = Mission G = General Public	E = Equipment F = Facilities V = Environment	J. Rufe 5 July 2019

Title: Electrical Failure							**Revision:** Initial				
Probability Interval: Battery Life	**Date:** 12 Jun 2019	**Affected Target**	**Risk Before Mitigations**			**Mitigations/Countermeasures**		**Risk After Mitigations**			**Verification**
System: Li-ion Battery	**Subsystem:** N/A										
Hazard Number/Description			Severity	Probability	RAC	D = Design E = Engineered Safety Feature S = Safety Device	W = Warning Device P/T = Procedures/Training	Severity	Probability	RAC	T=Test D=Demonstration I = Inspection A=Analysis
6.1 Electronic protection features of battery pack fail to operate causing damage to one or more battery cells which may result in an electrical failure. NOTE: This failure must occur in conjunction with another failure causing a challenge to the system for the hazard to occur		P G E F V	3	D	M	[S] - Provide a containment device adequate to contain any leaks, out-gassing, fire, and fragmentation. The containment device should also protect the battery cells from possible external energy stimulus that can potentially react with electrolyte.		3	E	M	T
			3	D	M	[S/P/T] – Personnel Protection Equipment (PPE) used by personnel to perform containment of damaged and/or defective battery cells		3	E	M	I
			3	D	M	[P/T] – Training curriculum provided on how to identify the proper PPE and equipment to be used to perform containment of damaged and/or defective battery cells		3	E	M	I
			3	D	M	[P/T] – Training curriculum provided to inform personnel on the procedures and proper use of equipment for containment of damaged and/or defective battery cells		3	E	M	I
			3	D	M	[P/T] - Provide inspection criteria of battery cells to screen for signs of potential hazards such as aging, electronic protection failures, etc.		3	E	M	I
6.2 Use of an incompatible battery charger causes damage to battery cell resulting in overtemperature and an electrical failure		P G E F V	3	C	M	[P/T] – Procedures for charging battery cells should identify the battery chargers or include a list of compatible alternative battery chargers that are approved for charging specific batteries		3	D	M	I
			3	C	M	[P/T] – Prohibit charging of battery cells during transport		3	D	M	I

Title: Electrical Failure						**Revision:** Initial				
Probability Interval: Battery Life / **Date:** 12 Jun 2019 **System:** Li-ion Battery / **Subsystem:** N/A **Hazard Number/Description**	**Affected Target**	**Risk Before Mitigations** Severity	Probability	RAC	**Mitigations/Countermeasures** D = Design; E = Engineered Safety Feature; S = Safety Device; W = Warning Device; P/T = Procedures/Training	**Risk After Mitigations** Severity	Probability	RAC	**Verification** T=Test D=Demonstration I = Inspection A=Analysis
6.3 Use of a defective battery charger causes damage to battery cell resulting in an electrical failure	P G E F V	3	C	M	[P/T] – Procedures for charging battery cells should identify the battery chargers or include a list of compatible alternative battery chargers that are approved for charging specific batteries	3	D	M	I
		3	C	M	[P/T] – Prohibit charging of battery cells during transport	3	D	M	I
6.4 A faulty battery design feature malfunction results in an electrical failure	P G E F V	3	D	M	[S] - Provide a containment device adequate to contain any leaks, out-gassing, fire, and fragmentation. The containment device should also protect the battery cells from possible external energy stimulus that can potentially react with electrolyte.	3	E	M	T
		3	D	M	[S/P/T] – Personnel Protection Equipment (PPE) used by personnel to perform containment of damaged and/or defective battery cells	3	E	M	I
		3	D	M	[P/T] – Training curriculum provided on how to identify the proper PPE and equipment to be used to perform containment of damaged and/or defective battery cells	3	E	M	I
		3	D	M	[P/T] – Training curriculum provided to inform personnel on the procedures and proper use of equipment for containment of damaged and/or defective battery cells.	3	E	M	I

Title: Electrical Failure							**Revision:** Initial				
Probability Interval: Battery Life	**Date:** 12 Jun 2019	**Affected Target**	**Risk Before Mitigations**				**Mitigations/Countermeasures**	**Risk After Mitigations**			**Verification**
System: Li-ion Battery	**Subsystem:** N/A		Severity	Probability	RAC		D = Design; E = Engineered Safety Feature; S = Safety Device; W = Warning Device; P/T = Procedures/Training	Severity	Probability	RAC	T=Test; D=Demonstration; I = Inspection; A=Analysis
Hazard Number/Description											
6.5 Discharging of battery packs at an excessive current (external short circuit) resulting in an electrical failure		P G E F V	3	C	M		All mitigations from 6.4	3	E	M	T
6.6 Charging of battery packs outside an acceptable temperature range occurs resulting in an electrical failure		P G E F V	3	C	M		[P/T] – Procedures for charging battery cells should identify the battery charger operational limits	3	D	M	I
			3	C	M		[P/T] – Prohibit charging of battery cells during transport	3	D	M	I
6.7 Over discharge of battery packs results in an electrical failure		P G E F V	3	C	M		All mitigations from 6.4	3	E	M	T

Title: Electrical Failure						**Revision:** Initial				
Probability Interval: Battery Life **System:** Li-ion Battery	**Date:** 12 Jun 2019 **Subsystem:** N/A	**Affected Target**	**Risk Before Mitigations**			**Mitigations/Countermeasures**	**Risk After Mitigations**			**Verification**
Hazard Number/Description			Severity	Probability	RAC	D = Design E = Engineered Safety Feature S = Safety Device W = Warning Device P/T = Procedures/Training	Severity	Probability	RAC	T=Test D=Demonstration I = Inspection A=Analysis
6.8 Latent damage to battery packs from repeated discharging of cells to 0V results in an electrical failure		P G E F V	3	C	M	All mitigations from 6.4	3	E	M	T
			3	C	M	[P/T] - Provide inspection criteria of battery cells to screen for signs of potential hazards such as aging, electronic protection failures, etc.	3	D	M	I
			3	C	M	[P/T] – All precautions from 49 CFR 173.185(f), including placement of each cell or battery in individual, non-metallic inner packaging that completely encloses the cell or battery, the use of surrounding cushioning material that is non-combustible, non-conductive, and absorbent, each inner packaging individually placed in an outer packaging that meets the applicable requirements of part 178, subparts L, M, P and Q at the Packing Group I level, and marking of the outer package with "Damaged/ defective lithium ion battery," as appropriate.	3	D	M	I

Prepared By/Date:	**Revised By/Date:**	**Target Codes:**		**Approved By/Date:**
J. Teter / R. Dittmar 12 June 2019	J. Delmonte 25 June 2019	P = Personnel M = Mission G = General Public	E = Equipment F = Facilities V = Environment	J. Rufe 5 July 2019

Title: Health Hazard						**Revision:** Initial				
Probability Interval: Battery Life **System:** Li-ion Battery	**Date:** 12 Jun 2019 **Subsystem:** N/A	**Affected Target**	**Risk Before Mitigations**			**Mitigations/Countermeasures**	**Risk After Mitigations**			**Verification**
Hazard Number/Description			Severity	Probability	RAC	D = Design E = Engineered Safety Feature S = Safety Device W = Warning Device P/T = Procedures/Training	Severity	Probability	RAC	T=Test D=Demonstration I = Inspection A=Analysis
7.1 Electrical exposure of personnel or equipment to high current or high voltage resulting in injury		P G E F V	2	D	M	[S] - Provide a containment device adequate to contain any leaks, out-gassing, fire, and fragmentation. The containment device should also protect the battery cells from possible external energy stimulus that can potentially react with electrolyte. [S/P/T] – Personnel Protection Equipment (PPE) used by personnel to perform containment of damaged and/or defective battery cells [P/T] – Training curriculum provided on how to identify the proper PPE and equipment to be used to perform containment of damaged and/or defective battery cells [P/T] – Training curriculum provided to inform personnel on the procedures and proper use of equipment for containment of damaged and/or defective battery cells	2	E	M	T
7.2 Personnel are burned from contact with high cell enclosure temperature caused by thermal runaway reactions from the battery packs.		P G E F V	2	D	M	All mitigations from 7.1	2	E	M	T
7.3 Exposure of personnel to damaged battery cells due to moisture causing electrolyte decomposition into Hydrogen Fluoride (HF) resulting in burns or deep tissue damage		P G E F V	1	D	S	All mitigations from 7.1	1	E	M	T

Title: Health Hazard						**Revision:** Initial				
Probability Interval: Battery Life	**Date:** 12 Jun 2019	**Affected Target**	**Risk Before Mitigations**			**Mitigations/Countermeasures**	**Risk After Mitigations**			**Verification**
System: Li-ion Battery	**Subsystem:** N/A									
Hazard Number/Description			Severity	Probability	RAC	D = Design E = Engineered Safety Feature S = Safety Device W = Warning Device P/T = Procedures/Training	Severity	Probability	RAC	T=Test D=Demonstration I = Inspection A=Analysis
7.4 Electronic protection features of battery pack fail to operate causing damage to one or more battery cells which may result in injury to personnel. NOTE: This failure must occur in conjunction with another failure causing a challenge to the system for the hazard to occur		P G E F V	2 2	D D	M M	All mitigations from 7.1 [P/T] - Provide inspection criteria of battery cells to screen for signs of potential hazards such as aging, electronic protection failures, etc.	2 2	E E	M M	T I
7.5 Discharging of battery packs at an excessive current level (external short circuit) results in an electrical failure		P G E F V	3	C	M	All mitigations from 7.1	3	E	M	T
7.6 Charging of battery packs outside an acceptable temperature range results in an electrical failure		P G E F V	3 3	C C	M M	[P/T] – Procedures for charging battery cells should identify the battery charger operational limits [P/T] – Prohibit charging of battery cells during transport	3 3	D D	M M	I I
7.7 Over discharge of battery packs results in an electrical failure		P G E F V	3	C	M	All mitigations from 7.1	3	E	M	T

Title: Health Hazard							**Revision:** Initial				
Probability Interval: Battery Life	**Date:** 12 Jun 2019	**Affected Target**	**Risk Before Mitigations**			**Mitigations/Countermeasures**	**Risk After Mitigations**			**Verification**	
System: Li-ion Battery	**Subsystem:** N/A		Severity	Probability	RAC	D = Design E = Engineered Safety Feature S = Safety Device W = Warning Device P/T = Procedures/Training	Severity	Probability	RAC	T=Test D=Demonstration I = Inspection A=Analysis	
Hazard Number/Description											
7.8 Latent damage induced into battery packs due to repeated discharging to 0V results in an electrical failure		P G E F V	3	C	M	All mitigations from 6.4	3	E	M	T	
			3	C	M	[P/T] - Provide inspection criteria of battery cells to screen for signs of potential hazards such as aging, electronic protection failures, etc.	3	D	M	I	
			3	C	M	[P/T] – All precautions from 49 CFR 173.185(f), including placement of each cell or battery in individual, non-metallic inner packaging that completely encloses the cell or battery, the use of surrounding cushioning material that is non-combustible, non-conductive, and absorbent, each inner packaging individually placed in an outer packaging that meets the applicable requirements of part 178, subparts L, M, P and Q at the Packing Group I level, and marking of the outer package with "Damaged/ defective lithium ion battery," as appropriate.	3	D	M	I	

Prepared By/Date:	**Revised By/Date:**	**Target Codes:**		**Approved By/Date:**
J. Teter / R. Dittmar 12 June 2019	J. Delmonte 25 June 2019	P = Personnel M = Mission G = General Public	E = Equipment F = Facilities V = Environment	J. Rufe 5 July 2019

6.3 MITIGATION AND COUNTERMEASURES

Based largely on the results of the PHL and PHA, the APT/SMS Team identified mitigations that are considered key to safely dealing with hazards that might be encountered during transport of damaged or defective Li-ion batteries. The team identified that while understanding the cause (source) of the hazard may be important for identifying the mechanisms of injury or damage to protect against, properly safing a device is mostly dependent upon proper identification of the hazard effect (outcome). This is largely because (1) many of the causes for Li-ion battery hazards are undetectable prior to an incident, and (2) the transportation configuration that a battery will be in when it creates a hazard cannot be predicted in advance. As such, procedural controls that should/could be applied prior to transport to limit the potential for a hazardous incident cannot be reliably expected to be in place.

For a proposed mitigation to be considered effective by the team, it needs to be effective for a wide variety of applications and products and against as many hazards as possible. It is anticipated that the mitigations will not be equally effective for all transportation modes or battery configurations. The proposed mitigation approaches listed in Table 6 were evaluated by the team via testing and further analysis.

As for the PHA, each mitigation/countermeasure is identified as either a design (D), engineered safety feature (E), safety device (S), warning device (W), or procedures/training (P/T) consideration, listed in order here by decreasing effectiveness. Procedures and training were combined since each is dependent upon human activity as a control and is more effective when accompanied by the other.

Table 6: Identified Key Mitigations

Mitigation	Applicable Transport Modes
[S] – Provide a containment device adequate to contain any leaks, out-gassing, fire, and fragmentation. The containment device should also protect the battery cells from possible external energy stimulus that can potentially react with electrolyte.	All
[S/P/T] – Personnel Protection Equipment (PPE) used by personnel to perform containment of damaged and/or defective battery cells.	All
[P/T] – Training curriculum provided on how to identify the proper PPE and equipment to be used to perform containment of damaged and/or defective battery cells.	All
[P/T] – Training curriculum provided to inform personnel on the procedures and proper use of equipment for containment of damaged and/or defective battery cells.	All
[E] – Provide a containment device that includes means of isolation between battery cells to reduce likelihood of physical contact between cell units.	All

Mitigation	Applicable Transport Modes
[P/T] - Provide inspection criteria for battery cells to screen for signs of potential hazards such as aging, electronic protection failures, etc.	Does not apply to passenger air
[P/T] – Prohibit charging of battery cells during transport.	All
[P/T] – Procedures should include steps that account for OEM recommended handling techniques and protocols to be followed for damaged and/or defective battery cells to ensure that batteries are handled with care and appropriate precautions are observed.	Highway, rail or water transport only
[P/T] – All precautions from 49 CFR 173.185(f), including placement of each cell or battery in individual, non-metallic inner packaging that completely encloses the cell or battery, the use of surrounding cushioning material that is non-combustible, non-conductive, and absorbent, each inner packaging individually placed in an outer packaging that meets the applicable requirements of part 178, subparts L, M, P and Q at the Packing Group I level, and marking of the outer package with "Damaged/ defective lithium ion battery," as appropriate.	Highway, rail or water transport only
[W] – Provide a gas detection system and warning system to notify personnel of out-gassing from a battery cell.	All
[P/T] – Procedures should include steps that specify the means to extinguish or dilute vented gases from damaged or defective battery cells.	All
[P/T] – Develop training curriculum to brief personnel on the procedures for extinguishing fire or diluting the vented gases discharged from damaged and/or defective battery cells.	All
[E] – Utilize packaging that does not contain components that are flammable.	Does not apply to passenger air
[E] – Develop criteria, methods, and techniques to maintain separation and isolation between multiple battery cells to reduce likelihood of propagation of an event in one cell to an adjacent battery cell.	Does not apply to passenger air
[P/T] – Procedures should include detailed steps to inspect for adequate separation and isolation between multiple battery cells to reduce likelihood of propagation of battery cell failure event.	Does not apply to passenger air

Some elements of the recommended protocols and methods have been derived from team member experience developing similar solutions for other applications and some of the information presented in this report was derived from manufacturer data (as noted). Recommendations for mitigations, protocols, and methods are focused upon functionality that is needed to safely control a hazard, not on features of any specific product(s).

PART III: TESTING

7.0 Testing

A series of tests were conducted to validate and verify the viability of proposed packaging solutions (methods) to enable safe transport of defective or damaged charge storage devices. The purpose of the testing was also to demonstrate whether the testing protocol proposed is reasonable for qualifying containment devices designed for use with damaged and defective charge storage devices. The following sections describe the tests, including their selection and design, the processes followed, pass/fail criteria used, significant events or findings, results, and observations or conclusions specific to the testing.

7.1 DESIGN OF TESTS

In accordance with the Statement of Work (SOW), all tests were performed to assess the ability to use containment to mitigate or ameliorate hazards realized during transportation as a result of damaged or defective Li-ion batteries. From the PHL and PHA performed in this project and presented previously in the Classification Protocol and Method Report, the Li-ion battery hazards identified by the team were grouped into the following failure modes:

1. Battery Cell Electrolyte Leakage
2. Outgassing
3. Explosion/Fragmentation
4. Fire/Heat
5. Thermal Runaway
6. Electrical Failure
7. Health Hazard

The team designed the testing to evaluate the characteristics needed in a containment device to address these failure modes and to determine whether existing containment devices are able to adequately mitigate or ameliorate the identified hazards. In addition, since battery containment devices will be subject to the same environmental stresses that batteries may see and are designed to contain any resulting hazards, it was decided that a starting point for developing a standard set of tests should be the battery tests outlined in Section 38.3, Lithium metal and lithium ion batteries, from the *UN Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria.*

7.1.1 Test Requirements

Using the PHA and PHL as a basis, the team developed requirements for features that should be exhibited by a battery container to control the identified hazards. These included:

- Ability to contain effluents (defined in Section 38.3.2.2 of the *UN Manual of Tests and Criteria* to be a liquid or gas)
- Ability to contain fire

- Ability to contain fragments
- Surfaces of the container should not reach levels that could burn personnel[45]
- Release of hazardous or corrosive material from the battery should be contained
- Batteries should be secure in the container and not loose where they may contact container interior surfaces
- If multiple batteries are contained, verification is required that an event from one battery will not propagate to an adjacent battery
- Protect the battery from external contamination that could initiate or exacerbate a thermal reaction
- The container materials of construction should be compatible with the battery, ensuring that a leak will not result in a subsequent reaction between the battery fluid and the container materials

Using these criteria, the team developed a test matrix to ensure that the containers tested could address the identified hazards. In some instances, a single test was used to address multiple hazards.

7.1.2 Test Objectives

The test procedures chosen were ones to ensure that containers housing hazardous materials (damaged or defective Li-ion batteries) can withstand normal conditions in all transportation modes. Each test was performed to determine whether the container is designed, manufactured, and assembled to successfully meet a portion of the criteria in Section 7.1.1, with the aggregate of the tests covering all of the identified requirements. Table 7 provides a summary of which tests are intended to verify the prescribed container requirements. Details of the tests conducted and of the pass/fail criteria applied are included in Section 7.3.

Table 7: Summary of Testing

Container Requirements	Procedure	Test Event	Pass Criterion
1. Ability to contain effluents	Water indicating paper placed inside the container before the test. Water sprayed on the container from multiple angles post-test.	Drop Vibration Altitude	Water indicating paper not activated
	No visible or detected outgassing	Thermal	Visual and sensory inspection

[45] A standard temperature threshold at which personnel may experience burns has not been established by OSHA or any other government agency. UL2200 *Standard for Stationary Engine Generator Assemblies* includes some recommended temperature limits for metallic and non-metallic items, with the lowest temperature listed as 122 °F. (50 °C). Industry typically accepts 140 °F (60 °C) as a minimum threshold at which burns can occur, assuming 5 seconds of exposure.

Container Requirements	Procedure	Test Event	Pass Criterion
2. Ability to contain fire	Water indicating paper placed inside the container before the test. Water sprayed on the container from multiple angles post-test.	Drop Vibration Altitude	Water indicating paper not activated
	Batteries tested to failure with no fire detected outside of the container	Thermal	Visual and sensory inspection
3. Ability to contain fragments	Batteries tested to failure with no fragments outside of container	Thermal	Visual and sensory inspection
4. Surfaces of the container will not reach levels that could burn personnel	Thermal test with simulated Li-ion battery (heater) inside container	Thermal	Container external surface temperature does not exceed 50 °C
5. Release of hazardous or corrosive material from the battery will be contained	Water indicating paper placed inside the container before the test. Water sprayed on the container from multiple angles post-test	Drop Vibration Altitude	Water indicating paper not activated
	No visible or detected leakage	Thermal	Visual and sensory inspection
6. Batteries will be secure in the container and not loose where they may contact container interior surfaces	Methods to secure batteries are provided	Drop Vibration	Visual inspection post-test to verify no shifting
7. If multiple batteries are contained in a single container, an event from one battery will not propagate to an adjacent battery	Methods to secure batteries or dividers between batteries are provided	Drop Vibration Thermal	Visual inspection post-test to verify the effectiveness of separation method(s)
8. The battery is protected from external contamination that could initiate or exacerbate a thermal reaction	Water indicating paper placed inside the container before the test. Water sprayed on the container from multiple angles post-test.	Drop Vibration Altitude	Water indicating paper not activated
9. Container materials are compatible with the battery, ensuring that a leak will not result in a subsequent reaction between the battery fluid and the container materials	No visible or detected changes to container surfaces that could indicate a chemical reaction	Thermal	Visual inspection

7.1.3 Tests

Figure 14 shows the flow followed in the test plan. This final test plan, which was coordinated with the PHMSA Contracting Officer's Representative (COR) and Subject Matter Expert (SME) prior to testing, was an evolution from the team's original test plan. The final test plan was derived using the original test plan as a starting point, modifying it in accordance with findings from the Design of Experiments (DOE). More tests were originally proposed than were performed as part of the final plan primarily because: 1) many of the tests originally proposed were redundant, evaluating the same factors and potential hazards as other tests, 2) some of the tests originally proposed did not address the specific hazards identified for Li-ion batteries, and 3) the capability of the containers to adequately address the identified hazards could be evaluated using fewer tests. The APT/SMS Team's preliminary (original) test plan is shown in Appendix A for reference.

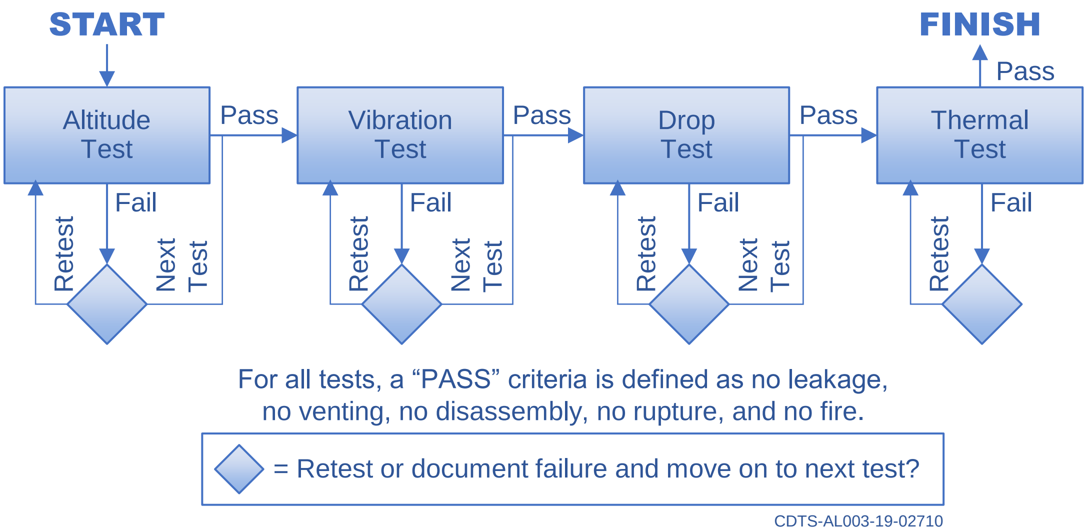


Figure 14: Test Plan Flow

The proposed tests in Figure 14 are designed to verify that a container will adequately contain the hazardous effects of a damaged or defective battery. The tests focus on the ability of the container to withstand various conditions, such as drops, altitude, vibration, and thermal stimulus without having its integrity compromised. In all of the tests, personnel visually verify whether a container contains any leaks, fragments, flames, and other hazards. Failure of a device in a test should result in a decision whether to re-perform the test or to continue, documenting the failure.

Pass/Fail Criteria

Figure 14 also highlights the criteria used to determine whether a containment device passes or fails each test. Since electrolyte leakage and outgassing are hazards to be considered, any breach in the outer surface of the containment device is considered a failure. Likewise, damage to the containment device that might preclude it from containing an identified Li-ion battery hazard for the duration of the transport mode is considered a failure.

Test 1: Altitude Test

The purpose of this test is to evaluate the effect of high-altitude conditions on containers for damaged or defective lithium ion batteries.

The sample container is tested at a pressure of 11.6 kPa for 6 hours, maintaining the temperature at 72 ± 3 °C. This pressure simulates an altitude of 51,000 feet. For containers designed to be watertight, water indicating paper is placed on the inside of the container prior to testing. One of each container is subjected to testing one time.

After 6 hours, the sample is removed and inspected for signs of damage. The container is also sprayed with water from multiple angles with the intention of having moisture penetrate the container, if possible. A “PASS” result is achieved if the container maintains its structural integrity and there are no holes, cracks, or other damage that would result in a loss of function of the packaging. For containers designed to be watertight, the water indicating paper must not be active for a “PASS” result.

For the detailed procedure, see Training Module SMS-5610 in Attachment 1 to Appendix A.

Test 2: Thermal Test

The purpose of this test is to evaluate the effect of high temperature thermal hazards associated with thermal runaway of a lithium ion battery on sample containers.

A small, high temperature heater inside a steel block is placed inside the sample container and heated to simulate a lithium ion battery pack. The heater is heated to a maximum temperature of 730 °C for two minutes. Thermocouples are used to monitor and record at least two separate areas inside the container and two areas on the external surface of the container. One of each container is subjected to testing.

After two minutes, the heater is turned off and the temperature is monitored for one hour. The container is then allowed to cool, and the container inspected for signs of damage. A “PASS” result is achieved if the container maintains its structural integrity, no holes or cracks are observed, and the external surface temperature of the container did not exceed 50 °C.

For the detailed procedure, see Training Module SMS-5610 in Attachment 1 to Appendix A.

Test 3: Vibration Test

The purpose of this test is to evaluate the effect of vibration during transport on containers.

The container is secured to a vibrating table and subjected to vibrations for six hours. For containers designed to be watertight, water indicating paper is placed on the inside of the container prior to testing. One of each container is subjected to testing one time.

Samples are inspected before and after testing to note any physical damage. The container is also sprayed with water from multiple angles with the intention of having moisture penetrate the container, if possible. A “PASS” result is achieved if the sample container maintains its structural integrity and there are no holes, cracks, or other damage that would result in loss of function of the packaging. For containers designed to be watertight, the water indicating paper must not be active for a "PASS" result.

For the detailed procedure, see Training Module SMS-5610 in Attachment 1 to Appendix A.

Test 4: Drop Test

The purpose of this test is to evaluate the effect of a free-fall impact on containers.

The sample is lifted to a height of 6 feet (1.8 meters) and dropped remotely. For containers designed to be watertight, water indicating paper is placed on the inside of the container prior to testing. One of each container is subjected to testing one time.

Samples are inspected before and after testing to note any physical damage. The container is also sprayed with water from multiple angles with the intention of having moisture penetrate the container, if possible. A "PASS" result is achieved if the sample container maintains its structural integrity and there are no holes, cracks, or other damage that would result in loss of function of the packaging. For containers designed to be watertight, the water indicating paper must not be active for a "PASS" result.

For the detailed procedure see, Training Module SMS-5610 in Attachment 1 to Appendix A.

7.2 ASSETS

7.2.1 Containment Devices

Testing was performed on four containment devices as part of this task:

- Lithium Fire Guard PG100 (formerly PlaneGard)
- Fire Containment Concepts 14" PED SAFE-PAK
- Newtex Z-Block Fire Containment Tote-Style Bag
- Brimstone Battery Fire Containment Bag

Each containment device had unique features identified as desirable to control hazards associated with a Li-ion battery in thermal runaway. However, research also identified that none of the containment devices was expected to possess all of the desired hazard control features. Testing was performed on one box-style and three bag-style containment devices.

The box style container tested was the *Lithium Fire Guard PG100*, which is designed to safe a PED that has gone into thermal runaway on an airplane. Lithium Fire Guard claims to be “the only 100% containment technology available,” stating that it fully contains and renders harmless the flames, heat, smoke, toxic fumes, and flammable vapors associated with a PED in thermal runaway. The PG100 design incorporates a scoop that is intended to allow the damaged or defective lithium ion battery to be placed in the containment device without a need to touch it. It is also designed to be used as a shield to protect the responder as he/she approaches the burning device. The shield is transparent since it is intended to provide full visibility of the device. The PG100 works by sliding the case open, placing the device in thermal runaway into the case, closing the case, and adding water into the container via a valve. The addition of water is intended to aid cooling of the devices and to extinguish any fires that may still be present. Two Lithium Fire Guard PG100 containment devices were used during testing.

Figure 15: Lithium Fire Guard PG100

The first of the bag-style containment device tested was the *Fire Containment Concepts 14” PED Safe-PAK*. Fire Containment Concepts advertises their containment design produces “the only commercial grade fire bag that both contains and suppresses lithium-ion battery fires.” Further, they tout that their system is the only one in the industry that contains and automatically suppresses on-board lithium-ion battery fires. Among the features of the 14” PED Safe-PAK are filtering vents, four (4) 4.5 oz. temperature-activated suppression bladders lining the interior walls, a UL-certified fire-resistant zipper, high temperature textiles, and triple seal technology.

Figure 16: Fire Containment Concepts 14” PED SAFE-PAK

The second bag-style containment device tested was the *Newtex Z-Block™ Fire Containment Tote-Style Bag*. The Tote-Style bag is 24" x 13" x 5" and features a flat bottom and 3-dimensional design that allows the bag to stand upright. Other features include two nylon carrying straps and a zipper closure. The bag is designed to contain fires caused by Li-ion batteries found in laptops, cell phones, tablets, and other personal electronic devices (PEDs). It is made with Newtex's Z-Block™ fire and smoke resistant fabrics, which are also used to fabricate cargo fire containment covers. Z-Block™ is advertised to exceed fire suppression performance standards set by FAA, European Aviation Safety Agency (EASA), and leading cargo carriers. It further boasts several layers of advanced Z-Block™ Flame Retardant Fabric, ZetexPlus® Vermiculite Coated Fiberglass Fabric, and Z-Flex® Aluminized Fabric to ensure heat and fire remain contained. It is reported that the fabrics will not burn, melt, or allow flame penetration; are resistant to molten metal burn-through; will withstand temperatures up to 1,800 °F (980 °C); are watertight and chemical resistant; will not support growth of mold, fungi, and bacteria; are unaffected by extreme temperature or UV; and are abrasion, puncture, and tear resistant.

Figure 17: Newtex Z-Block™ Fire Containment Tote-Style Bag

The third bag-style containment device tested was the *Brimstone Battery Fire Containment Bag - Large (Laptop) - Preventer™ Edition*. Brimstone asserts in their literature that this containment device has been shown in testing to contain 10,000 mAh thermal runaway events. The bags are made from patented materials that contain a layer of Kevlar in case an explosive event creates projectiles traveling at ballistic velocities. The device's carbon liner has a temperature rating of 3,000 °F, with a second layer designed to withstand temperatures above 2,200 °F for sustained periods of time. Brimstone further cites that the materials used in their bags have been FAA certified and that tests of the devices were conducted in accordance with Title 14 CFR Part 25 – Subpart D, § 25.853 (a) compartment interiors [Amdt. 25-116, 69 FR 62788, Nov 26, 2004] Appendix F to Part 25, Part I (a)(1)(ii) [Amdt. 25-111, Eff. 9/2/2003] and are FAA Compliant. The bag is designed based on the concept that rapidly expanding gases released during a Li-ion battery thermal runaway will cause a containment bag to expand like a

Figure 18: Brimstone Battery Fire Containment Bag - Large (Laptop) - Preventer™ Edition

balloon. As such, to avoid Velcro closures pulling apart and releasing potentially dangerous gases, debris, and flame, Brimstone's design incorporates a pull-over flap.

One article of each of the three bag-style containers was used in testing.

7.2.2 Test Facilities

Multiple test facilities were used to perform the testing. The altitude and vibration tests were performed at the Rocky Mountain Testing Solutions Environmental Lab in Pleasant View, UT. The other tests were performed at Tooele Army Depot (TEAD), SMS's partnered test site for large-scale and small-scale tests of substances and articles. Below are some of the features of the test site.

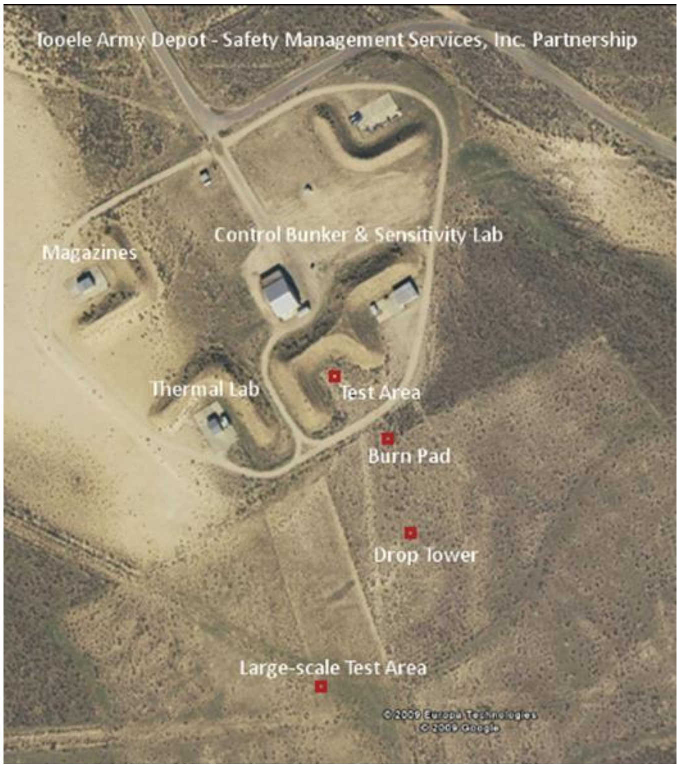


Figure 19: SMS's Test Site

- 94-acre dedicated test area
- 24/7 secured, restricted-access location
- Sensitivity lab with impact, friction, electrostatic discharge (ESD), and Simulated Bulk Auto-Ignition Test (SBAT) apparatuses
- Extensive auxiliary equipment support including:
  - High-speed video
  - Radiometry (heat-flux) measurement
  - Reflective and side-on overpressure measurement
  - High definition video
  - Internal pressure measurement
  - Detonation velocity measurement
- Remote 12-meter (40-foot) drop tower
- High and low temperature conditioning chambers

7.2.3 Instrumentation

Instrumentation required for the testing was minimal. The drop and vibration tests did not require instrumentation. The altitude testing used Type-K thermocouples and pressure sensors. Thermocouples were used in the thermal test (both external and internal to the container). The thermal test also used a heating block to simulate a heat source from which failure could propagate to the batteries by increasing the battery temperature.

7.2.4 Batteries

The batteries used in the testing were Sony VTC6 18650 3000mAh 30A Discharge 3.7v rechargeable batteries (see Figure 20), which are used in high-demand power packs and battery packs with electronic protection circuits, and are not for stand-alone use. These batteries are cylindrical lithium-ion batteries approximately 65 mm in length with a diameter of 18 mm. The 18650 batteries were chosen as the test batteries due to their use in a wide range of laptop batteries, battery power banks, e-cigarettes, and other portable electronic devices, including in Tesla vehicles. An 18650 battery is also of similar chemical composition, mAh, and voltage to an average cellphone battery.

Figure 20: Sony VTC6 18650 3000mAh 30A Discharge 3.7V Rechargeable Batteries

The batteries were only used in the thermal testing since the other tests focused on evaluation of the containers and the test results are independent of battery failure. In the thermal testing, a heater block was used to provide the heating source to initiate thermal runaway in the batteries.

7.2.5 Other Assets

Assets involved in the testing, aside from the two test facilities, batteries, test containers, and instrumentation (thermocouples and pressure sensors) previously discussed, included the following:

- Heating block (used in thermal test)
- Water indicating paper (used in drop test, vibration test, and altitude test)
- Hoist and cement pad (used in drop test)
- L.A.B. Transportation Simulation Shaker (Rotary Vibration) (Model Number: 4000V, Serial Number 241164) (used in vibration test)
- Russells Altitude Chamber (Model Number: RHB-13-5-5-WC, Serial Number 04063710) (used in altitude test)

7.3 TEST PROCEDURES

The following sections outline the procedures that were followed for each test.

7.3.1 Altitude Testing

Altitude testing was performed in accordance with Section 38.3.4.1, Test T.1 – Altitude simulation from the *UN Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria*. The test is designed to simulate the effects inside an airplane if there is an immediate pressure loss and is intended for use on batteries to determine whether altitude can cause battery mass loss, leakage, venting, disassembly, rupture, fire or open circuit voltage loss. However, for the purposes of this project, the test was performed to evaluate the effect of high-altitude conditions on damaged or defective lithium-ion battery containers. This was to evaluate whether any of the features of the containers could become compromised by pressure changes like those that could be experienced in flight.

The sample containers were tested at a pressure of 87 Torr (11.6 kPa) for 6 hours. This pressure simulates an altitude of 51,000 feet. The ambient room temperature was maintained at 73 ± 18 °F (23 ± 10 °C) with a relative humidity of 40% ± 30%. The testing temperature was ramped and maintained at 162 ± 5 (72 ± 3 °C) for 6 hours. Water indicating paper was placed on the inside of each container prior to testing.

After 6 hours, the containers were removed and inspected for signs of damage. The containers were also sprayed with water from multiple angles. A "PASS" result was earned if the sample container maintained its structural integrity and there were no holes, cracks, or other damage that would result in loss of function of the packaging. For containers designed to be watertight, a "PASS" result was only issued if the water indicating paper was not activated.

None of the devices used to contain hazards from damaged or defective charge storage devices are expected to be hermetically sealed against outgassing of small particles. In addition, evaluation criteria for the tests in Section 38.3 of the *UN Manual of Tests and Criteria* do not specify a method to determine whether leakage or venting of effluents occurs. As such, the team opted to use the combination of an exterior water spray and water indicating paper internal to the container to identify whether a path exists post-test for moisture to enter a container, which would also indicate a path for effluents to escape.

The detailed procedure is included in Appendix A.

7.3.2 Vibration Testing

The team used Method A2 – Repetitive Shock Test (Rotary Motion) in ASTM D999, *Standard Test Methods for Vibration Testing of Shipping Containers* as a guide for vibration testing. The container was placed on a rotary vibration table and underwent one hour of vibration at 280 RPM. In order to impart the maximum force on the container, isolating it from any dampening by the table, the container was raised from the rotary vibration table so that a shim with a 1.6 mm (1/16 in.) thickness and a width of 50 mm (2.0 in.) was able to pass between the bottom of the package and the rotary vibration table.

Immediately following the period of vibration, the container was removed from the platform, turned on its side and observed for any evidence of leakage. A container passed the vibration test if there was no rupture or path for leakage from the container. Also, to pass, a container should have no sign of deterioration that could adversely affect safe transportation or any distortion liable to reduce container strength.

The detailed procedure is included in Appendix A.

7.3.3 Drop Test

The team used MIL-STD-810G, *Environmental Engineering Considerations and Laboratory Tests* as a standard for the drop test since it is the most widely used international standard to test ruggedness and reliability of equipment when exposed to environmental stresses like those associated with transportation. Its intent is to identify deficiencies, shortcomings, and defects in equipment design, materials, manufacturing processes, packaging techniques, and maintenance methods.

A container was dropped from a height of 6 feet (1.8 meters) in the orientations listed in Table 8. The target was a rigid, non-resilient, flat, and horizontal surface.

Table 8: Test Configurations

Container	Number of Tests	Drop Orientation of Samples
Lithium Fire Guard PG100	1	Flat on the side
	1	Flat on the bottom
Fire Containment Concepts 14” PED SAFE-PAK	1	Flat on the side
	1	Flat on the bottom
Newtex Z-Block™ Fire Containment Tote-Style Bag	1	Flat on the side
	1	Flat on the bottom
Brimstone Battery Fire Containment Bag	1	Flat on the side
	1	Flat on the bottom

Containers were inspected before and after testing to note any physical damage. Each container was also sprayed with water from multiple angles. A “PASS” result was earned if the sample container maintained its structural integrity and there were no holes, cracks, or other damage that would result in loss of packaging function. For containers designed to be watertight, a “PASS” result was only issued if the water indicating paper was not activated.

As previously stated, none of the devices used to contain hazards from damaged or defective charge storage devices were expected to be hermetically sealed against outgassing of small particles and the evaluation criteria in Section 38.3 of the *UN Manual of Tests and Criteria* do not specify a method to determine whether leakage or venting of effluents occurs. As such, the team opted to use the combination of an exterior water spray and water indicating paper internal to the container to identify whether a path existed post-test for moisture to enter a container, which would also indicate a path for effluents to escape.

The detailed procedure is included in Appendix A.

7.3.4 Thermal Testing

The purpose of this test was to evaluate the effect of high temperature thermal hazards associated with thermal runaway of a lithium-ion battery on a sample container. The test conducted was a non-standard test, specifically designed to induce thermal runaway in the batteries. The test on each container was run in two parts.

In the first part of the test, a small, high temperature heater inside a steel block designed to simulate a lithium-ion battery pack was placed inside the sample container and heated. The heater was heated to a maximum temperature of 388 °C for 2 minutes. Thermocouples were used to monitor and record at least two separate areas inside the container and two areas on the external surface of the container.

Figure 21 and Figure 22 show the locations of the thermocouples for the thermal test.

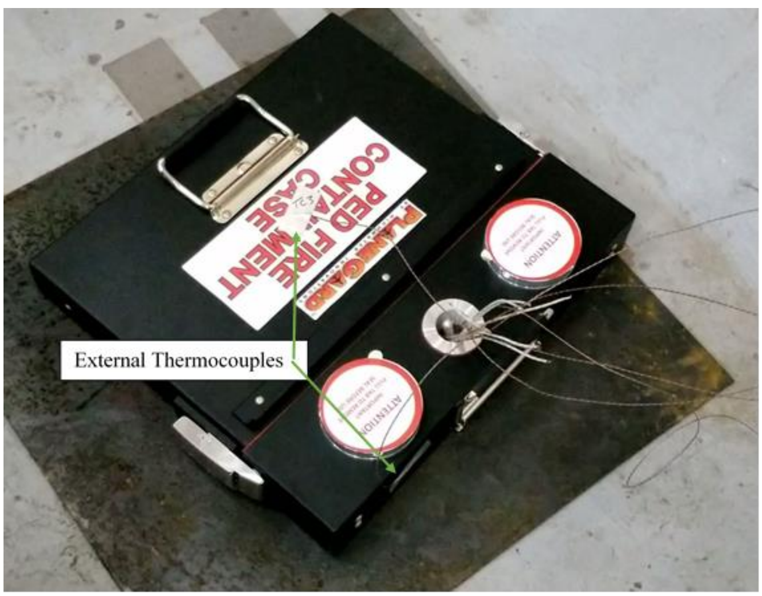


Figure 21: External Thermocouples – Pre-Test

Figure 22: Internal Thermocouples – Pre-Test

After two minutes, the heater was turned off and the temperature was monitored for one hour. The container was allowed to cool, and the sample container inspected for signs of damage. A “PASS” result was achieved if the sample container maintained its structural integrity, no holes or cracks were observed, and the external surface temperature of the container did not exceed 50 °C (122 °F).

Upon completion of the first part of the thermal testing using the high temperature heater, Li-ion batteries were inserted into the container for the second part of the test. The same testing protocol was then run using the heater block and Li-ion batteries, with the same pass/fail criteria.

The detailed procedure is included in Appendix A.

7.3.5 Test Schedule/Timeline

Table 9 shows the dates of the testing.

Table 9: Summary of Testing

Test	Scheduled Test	Notes
Drop test	November 5, 2019 and April 29, 2020	The tests were performed at SMS test facilities. The Lithium Fire Guard PG100 containers did not pass the test due to damage that resulted from the drop. All other containers passed the test.
Vibration test	November 7, 2019 and May 11, 2020	The testing was performed at Rocky Mountain Testing Solutions. All of the containers passed the test.
Altitude test	November 7, 2019 and May 18, 2020	The testing was performed at Rocky Mountain Testing Solutions. All of the containers passed the test.
Thermal test	November 26, 2019, December 12, 2019, June 2, and June 10, 2020	The testing was performed at SMS test facilities. For the Lithium Fire Guard PG100, additional testing was performed since the first test caused the container to melt. Thermal testing was only performed once on the three lithium battery containment bags. All four containers failed this test.

8.0 Post-Test Data Analysis and Reduction

The following sections present the results of the tests along with the team's interpretation of each.

8.1.1 Altitude Test

No leakage was observed from the tested containers. No damage was observed that would adversely affect the safety and functionality of the shipping containers. (Figure 23 through Figure 25)

Figure 23: Altitude Test Setup (November 7, 2019)

Figure 24: Test Article Post Test (November 7, 2019)

Figure 25: Altitude Test Setup (May 18, 2020)

All four of the tested containers passed the test without incident.

8.1.2 Vibration Test

No leakage was observed from any of the containers after test completion. No damage was observed that would adversely affect the safety or functionality of the shipping containers. (Figure 26 through Figure 28)

Figure 26: Vibration Test Setup (November 7, 2019)

Figure 27: Test Article Post Test (November 7, 2019)

Figure 28: Vibration Test Setup (May 11, 2020)

8.1.3 Drop Test

After the first test on the Lithium Fire Guard PG100, it was noted that the container suffered cracking, which would allow material inside of the container to escape (see Figure 29). The second test did not damage the container, but the latches that secured the container opened upon impact (see Figure 30).

Figure 29: Cracking Sustained by the Container After the First Drop Test in the Lithium Fire Guard PG100

Figure 30: Open Latches After the Second Drop Test in the Lithium Fire Guard PG100

The other three containers had no damage in any of the tests and all passed the test. Figure 31 through Figure 36 show the tests conducted on the other containers.

Figure 31: Fire Containment Concepts 14" PED SAFE-PAK Drop Test Setup

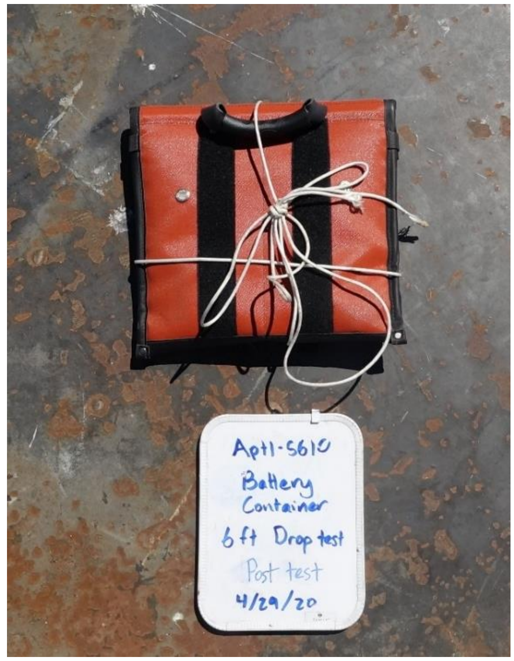


Figure 32: Fire Containment Concepts 14" PED SAFE-PAK Drop Test Result

Figure 33: Newtex Z-Block™ Fire Containment Tote-Style Bag Drop Test Setup

Figure 34: Newtex Z-Block™ Fire Containment Tote-Style Bag Drop Test Result

Figure 35: Brimstone Battery Fire Containment Bag Drop Test Setup

Figure 36: Brimstone Battery Fire Containment Bag Drop Test Result

8.1.4 Thermal Test

The two-part test was run twice on the Lithium Fire Guard PG100. In the first part of the first test, a heating block was placed in the test container to simulate a battery in thermal runaway. As the heating block ramped up to test temperature, the external temperature of the container closely matched its temperature. When the block reached a temperature of 90 °C (approximately 2 minutes of steadily increasing the temperature) the outer surface of the container reached 87 °C. At this time, smoke became visible and the test area was filled with the smell of burning plastic, so the test was stopped.

The test was not run on the first test article with batteries due to damage to the case from the initial test (heating block only). Figure 37 shows two views of the damage to the Lithium Fire Guard PG100 case.

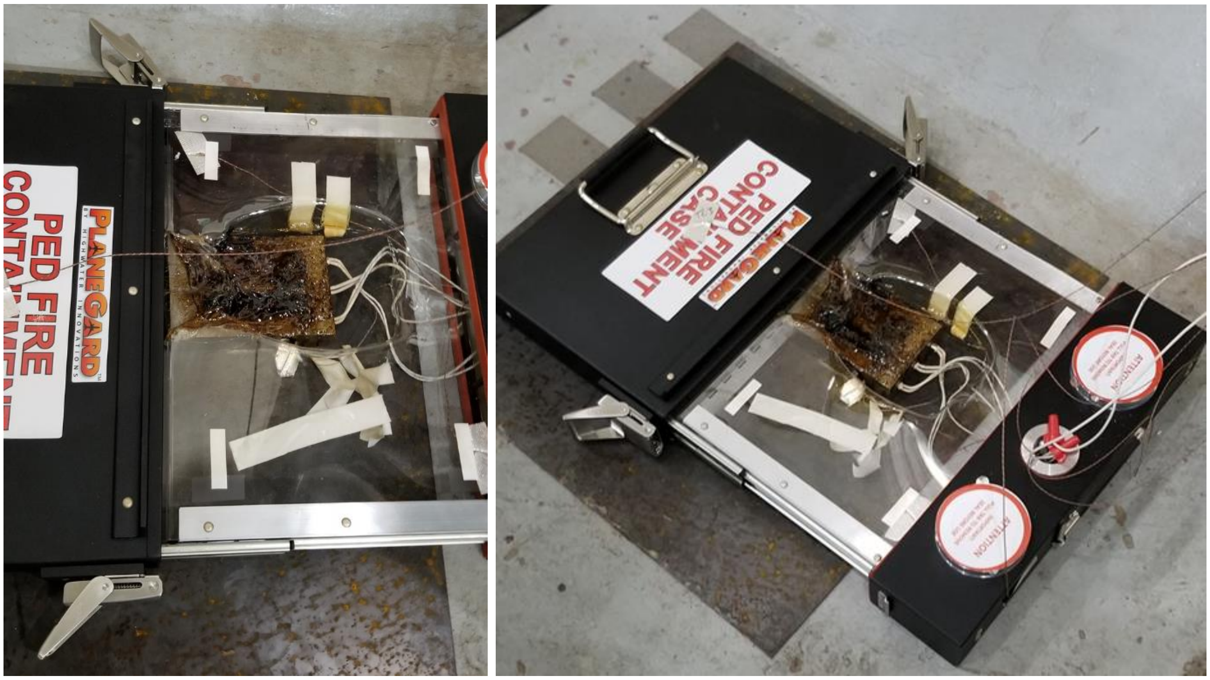


Figure 37: Melted/Burned Internal Plastic – Post Test

The same test was run with a second Lithium Fire Guard PG100 container, with the plastic parts that melted in the first test removed from the second test article. In the second test, the test was run to battery failure with no issues. Battery failure was evident through visual and auditory means. These included audible rushing of gases, burning, and charring of the battery casing, and removal of the terminal cover from outgassing. Figure 38 displays the batteries after the second test with the Lithium Fire Guard PG100. While the container was able to contain the effects of the battery during the second test, it was deemed to have failed the test due to the high external surface temperatures measured on the container, which were as noted earlier.

Figure 38: Batteries After Failure in Thermal Test

Thermal testing was performed on the three bag-style lithium battery containment bags. As mentioned previously, the bags tested were the PED Safe-PAK PSP-14, Brimstone Battery Fire Containment Bag Preventer Edition, and Z-Block Fire Containment Bag. Each bag was run through the two separate thermal tests as described previously and testing was done in the same manner as performed on the Lithium Fire Guard PG100. One test was performed to simulate battery runaway, which was run in each of the lithium battery bags with only the heating element. The first thermal test, involving just the thermal element, was run to the temperature where battery failure was expected. This was followed by a separate test with lithium batteries in close proximity to the heating element. The testing with the batteries and the heating element combination was run until battery failure. Each test produced similar failure results, which included burning and charring of the battery and containment. The PED Safe-Pack was equipped with a double sealed top and a layered gas containment system, including chemical bladders, which absorbed some of the heat and outgassing of the lithium batteries. The Z-Block Containment bag and the Brimstone Battery Bag lacked additional containment systems. However, only the Brimstone Battery Bag failed to contain the outgassing.

Figure 39: Post Test Image for Z-Block Bag (Left) and Brimstone Preventer Bag (Right)

Figure 40: Post Test Image for PED Safe-PAK

9.0 Container-Specific Observations/Findings

The Fire Guard PG100 container did not pass the drop test due to cracking that occurred and the fact that the latches did not remain secure during the drop. Such occurrences could allow hazardous material associated with defective and damaged charge storage devices to be released, thereby endangering personnel and other equipment in the area. All of the other containers passed the drop test.

For the altitude and vibration tests, all of the containers passed without any problems observed.

With regard to the use of a water spray with water indicating paper, it is recommended that, as part of a standard testing methodology, this indicator of a container's ability to contain effluents be performed pre-test as a baseline before the drop, altitude, and vibration tests, and again post-test for each.

In the thermal test, because the Fire Guard PG100 container melted and testing was not continued, the initial test was classified as a "FAIL." However, the container did contain the melting plastic and if a battery had been present, it appeared that the damaged battery would have been similarly contained.

In the second thermal test on the Fire Guard PG100, with the plastic parts removed and the test run to battery failure, all hazards from the failed batteries were contained. However, because the external surface temperature of the container was hot enough in both tests to cause burns, both tests were considered "FAIL."

For the PED Safe-PAK, when the thermal test was run to battery failure, all non-thermal hazards from the failed batteries were contained. The additional chemical bladders inside the pack helped contain the gases but failed to sufficiently contain the heat of the reaction. The external surface temperature of the container got hot enough to cause burns. Therefore, despite containing the battery's outgassing, the container received a "FAIL" for this test.

The Newtex Z-Block™ was subjected to the same testing and all non-thermal hazards were contained. However, as with the PED Safe-PAK, the Newtex external surface temperature became hot enough to cause burns. Due to the elevated external temperatures, the container received a "FAIL" for this test.

The Brimstone Battery Fire Containment Bag was subjected to the same testing and the majority of non-thermal hazards were contained. The external surface temperature became hot enough to cause burns and the outgassing was not contained within the bag. Due to the temperature results and failure to contain outgassing the container received a "FAIL" grade.

None of the containers tested included dividers or any other means to secure batteries from moving within the containers, thereby preventing impact with interior surfaces or hazards from one battery propagating to other batteries if more than one is placed inside. The presence or absence of a means to secure batteries in a container is verified by inspection and is not specifically tied to any of the four tests in the recommended methodology.

Table 10 through

Table 13 summarize by container the demonstrated ability to adequately control hazards from the nine failure modes listed in Table 7.

Table 10: Results of Testing on Lithium Fire Guard PG100

Container Test Requirements	Test Results (Pass/Fail)	Container Meets Requirement (Yes/No)
1. Ability to contain effluents	Drop – Fail Vibration – Pass Altitude – Pass Thermal – Fail	No
2. Ability to contain fire	Drop – Fail Vibration – Pass Altitude – Pass Thermal – Fail	No
3. Ability to contain fragments	Thermal – Fail	Yes*
4. Surfaces of the container will not reach levels that could burn personnel	Thermal – Fail	No
5. Release of hazardous or corrosive material from the battery will likely be contained	Drop – Fail Vibration – Pass Altitude – Pass Thermal – Fail	No
6. Batteries will be secure in the container and not loose where they may contact container interior surfaces	Drop – Fail Vibration – Pass	No
7. If multiple batteries are contained in a single container, an event from one battery will not likely propagate to an adjacent battery	Drop – Fail Vibration – Pass Thermal – Fail	No
8. The battery is protected from external contamination that could initiate or exacerbate a thermal reaction	Drop – Fail Vibration – Pass Altitude – Pass	No
9. Container materials are compatible with the battery, ensuring that a leak is not likely to result in a subsequent reaction between the battery fluid and the container materials	Drop – Fail Vibration – Pass Altitude – Pass Thermal – Fail	Yes

* Although the container failed the thermal test, the device's ability to contain fragments was not shown to be compromised.

Table 11: Results of Testing on Fire Containment Concepts 14" PED SAFE-PAK

Container Test Requirements	Test Results (Pass/Fail)	Container Meets Requirement (Yes/No)
1. Ability to contain effluents	Drop – Pass Vibration – Pass Altitude – Pass Thermal – Pass	Yes
2. Ability to contain fire	Drop – Pass Vibration – Pass Altitude – Pass Thermal – Pass	Yes
3. Ability to contain fragments	Thermal – Pass	Yes
4. Surfaces of the container will not reach levels that could burn personnel	Thermal – Fail	No
5. Release of hazardous or corrosive material from the battery will likely be contained	Drop – Pass Vibration – Pass Altitude – Pass Thermal – Pass	Yes
6. Batteries will be secure in the container and not loose where they may contact container interior surfaces	Drop – Pass Vibration – Pass	Yes
7. If multiple batteries are contained in a single container, an event from one battery will not likely propagate to an adjacent battery	Drop – Fail Vibration – Pass Thermal – Fail	No
8. The battery is protected from external contamination that could initiate or exacerbate a thermal reaction	Drop – Pass Vibration – Pass Altitude – Pass	Yes
9. Container materials are compatible with the battery, ensuring that a leak is not likely to result in a subsequent reaction between the battery fluid and the container materials	Drop – Pass Vibration – Pass Altitude – Pass Thermal – Fail	Yes

Table 12: Results of Testing on Newtex Z-Block™ Fire Containment Tote-Style Bag

Container Test Requirements	Test Results (Pass/Fail)	Container Meets Requirement (Yes/No)
1. Ability to contain effluents	Drop – Pass Vibration – Pass Altitude – Pass Thermal – Pass	Yes
2. Ability to contain fire	Drop – Pass Vibration – Pass Altitude – Pass Thermal – Pass	Yes

Container Test Requirements	Test Results (Pass/Fail)	Container Meets Requirement (Yes/No)
3. Ability to contain fragments	Thermal – Pass	Yes
4. Surfaces of the container will not reach levels that could burn personnel	Thermal – Fail	No
5. Release of hazardous or corrosive material from the battery will likely be contained	Drop – Pass Vibration – Pass Altitude – Pass Thermal – Pass	Yes
6. Batteries will be secure in the container and not loose where they may contact container interior surfaces	Drop – Pass Vibration – Pass	Yes
7. If multiple batteries are contained in a single container, an event from one battery will not likely propagate to an adjacent battery	Drop – Fail Vibration – Pass Thermal – Fail	No
8. The battery is protected from external contamination that could initiate or exacerbate a thermal reaction	Drop – Pass Vibration – Pass Altitude – Pass	Yes
9. Container materials are compatible with the battery, ensuring that a leak is not likely to result in a subsequent reaction between the battery fluid and the container materials	Drop – Pass Vibration – Pass Altitude – Pass Thermal – Pass	Yes

Table 13: Results of Testing on Brimstone Battery Fire Containment Bag

Container Test Requirements	Test Results (Pass/Fail)	Container Meets Requirement (Yes/No)
1. Ability to contain effluents	Drop – Pass Vibration – Pass Altitude – Pass Thermal – Fail	No
2. Ability to contain fire	Drop – Pass Vibration – Pass Altitude – Pass Thermal – Pass	Yes
3. Ability to contain fragments	Thermal – Pass	Yes
4. Surfaces of the container will not reach levels that could burn personnel	Thermal – Fail	No
5. Release of hazardous or corrosive material from the battery will likely be contained	Drop – Pass Vibration – Pass Altitude – Pass Thermal – Pass	Yes

Container Test Requirements	Test Results (Pass/Fail)	Container Meets Requirement (Yes/No)
6. Batteries will be secure in the container and not loose where they may contact container interior surfaces	Drop – Pass Vibration – Pass	Yes
7. If multiple batteries are contained in a single container, an event from one battery will not likely propagate to an adjacent battery	Drop – Fail Vibration – Pass Thermal – Fail	No
8. The battery is protected from external contamination that could initiate or exacerbate a thermal reaction	Drop – Pass Vibration – Pass Altitude – Pass	Yes
9. Container materials are compatible with the battery, ensuring that a leak is not likely to result in a subsequent reaction between the battery fluid and the container materials	Drop – Pass Vibration – Pass Altitude – Pass Thermal –Pass	Yes

10.0 Testing Conclusions

As stated previously, the purpose of the testing was to demonstrate whether the testing protocol proposed is reasonable for qualifying containment devices designed for use with damaged and defective charge storage devices, not to test the capability of the tested devices. The test results demonstrated the viability of the testing protocol. When a container did not pass a test, it highlighted areas for potential improvement in the container design in order to adequately address the full gamut of hazards identified for Li-ion batteries.

Table 14 presents a summary of the container requirements that were previously derived by the team and an assessment of whether the prescribed testing that was performed is sufficient to evaluate whether a container meets each requirement. The proposed tests were effective to assess a candidate containment device's ability to meet the prescribed container test requirements. Potential modifications to the tests are recommended in Section 12.0 for inclusion in a standard test method.

Table 14: Effectiveness of Testing to Assess Candidate Containment Devices

Container Test Requirements	Effective to Assess Candidate Containment Devices
1. Ability to contain effluents	Yes
2. Ability to contain fire	Yes
3. Ability to contain fragments	Yes
4. Surfaces of the container will not reach levels that could burn personnel	Yes
5. Release of hazardous or corrosive material from the battery will be contained	Yes
6. Batteries will be secure in the container and not loose where they may contact container interior surfaces	Yes

Container Test Requirements	Effective to Assess Candidate Containment Devices
7. If multiple batteries are contained in a single container, an event from one battery will not propagate to an adjacent battery	Yes
8. The battery is protected from external contamination that could initiate or exacerbate a thermal reaction	Yes
9. Container materials are compatible with the battery, ensuring that a leak will not result in a subsequent reaction between the battery fluid and the container materials	Yes*

* This should be supported by chemical analysis performed by the manufacturer during the design stage and containers should be labeled to indicate the charge storage devices for which they are intended.

PART IV: RECOMMENDATIONS

11.0 Recommendations for Classification of Defective and Damaged Charge Storage Devices

Safe transport of damaged or defective charge storage devices is predicated on three elements:

1. Proper classification of the devices following an established classification protocol,
2. Proper handling and packaging of the devices using an appropriate classification methodology, and
3. Equipment designed to effectively control the hazards of a charge storage device that becomes damaged or defective in transit.

Recommendations for accomplishing each of these are presented in the following sections.

11.1 RECOMMENDED CLASSIFICATION PROTOCOL

One of the goals of the project was to develop a classification protocol that laypersons, with little to no training, can use to classify the predominant Li-ion battery hazard(s) with which they are confronted, and successfully identify the steps needed to safe a defective or damaged Li-ion battery for continued transport. Figure 41 presents the recommended protocol that has been developed. This classification protocol was initially developed by the team for use on a passenger aircraft but, after analysis, has been determined to be appropriate for use in all transportation modes.

In the classification protocol shown in Figure 41, before handling the defective or damaged item, personnel are to obtain the equipment needed to safely handle the battery, which includes the following:

- Containers specifically designed and empirically proven via the recommended testing methods from Section 12.0 to control the hazard from damaged or defective charge storage devices
- Gloves for protection against heat or corrosive liquids
- Eye protection

Prior to handling a suspect Li-ion battery or any device that may contain one, personnel should don personal protection equipment (PPE).

After donning PPE, the first step to implementing the protocol is to check if the battery is installed in or connected to another device. If it is, personnel should determine if the assembled device fits in the protective container. If it does, the entire device should be placed in the protective container without handling the battery separately. If it does not, personnel should remove the battery (if possible), and then check for signs of battery rupture, such as swelling or hissing.

If the battery shows signs of potential rupture, it should be placed in a container specifically designed and empirically proven via the recommended testing methods from Section 12.0 to control battery fragmentation hazards and stored in a remote location. If the battery does not show signs of rupture, personnel should check to see if the battery is hot or leaking. If it is hot, it should be placed in the container and stored. If it is leaking, an additional step is needed to better ensure safety, which is that personnel should either seal the battery in the container and then place the entire container into a sealed secondary outer container designed to contain battery effluents or use a container that is designed to contain effluents, heat, and fragmentation.

If the battery cannot be removed from the device and the device will not fit into the protective container, the device should be isolated or removed from the transport vehicle (if possible) in order to prevent propagation to other devices and to limit the effects of any hazards. To achieve isolation, personnel should seek to place a barrier and/or create distance between the defective or damaged item and other assets that can be negatively affected by it or could exacerbate its failing state.

As described in the preceding paragraphs, the recommended classification protocol consists of steps to be taken to identify the Li-ion battery hazards that are presented in a given situation. The recommended classification methodology consists of methods to safely control the hazards. As such, the two are closely related and the flow in Figure 41 incorporates elements of both.

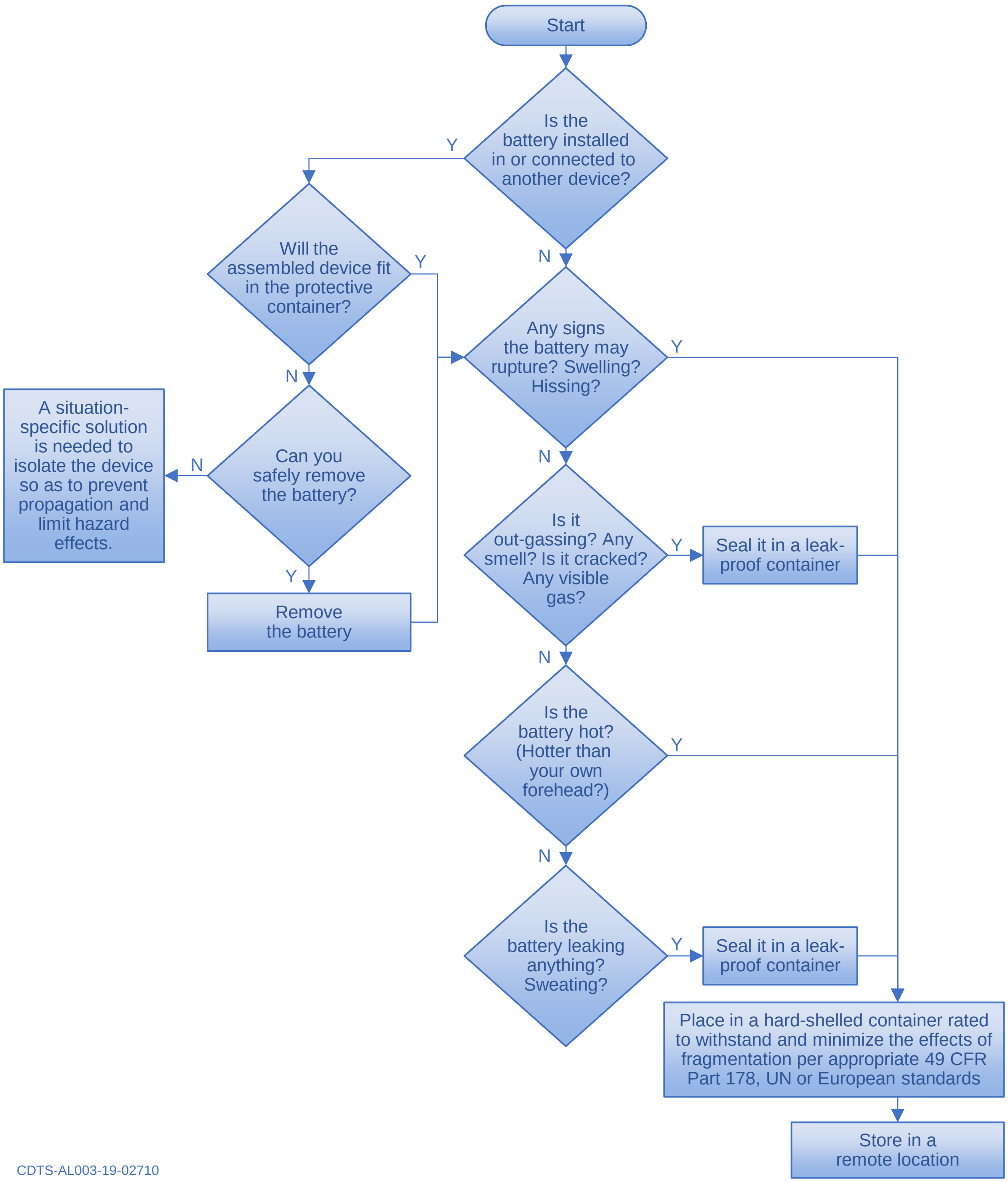


Figure 41: Classification Protocol/Methodology for Defective or Damaged Lithium Ion Batteries

It may be obvious, but one of the foundational prerequisites for using this recommended protocol is awareness that a charge storage device has become damaged or is defective. This is one of the potential differences among the different transportation methods since during marine, rail, cargo aircraft or truck transportation, detection of an issue may be less likely than in the cabin of a passenger aircraft. That difference does not impact the applicability of the recommended classification protocol but could render it useless if an issue is not detected and it is never implemented. Potential solutions to this challenge are discussed in Section 13.0.

11.2 CLASSIFICATION METHODOLOGY RECOMMENDATIONS

Based on the hazards identified in the PHL and PHA, a classification method was developed. Since the focus of this study was on the potential to contain hazards from damaged and defective charge Li-ion batteries, the classification method is intended to be a simple procedure with dedicated equipment that can be used to safely mitigate or ameliorate the realization of these hazards when encountered during transportation. So, as previously stated, Figure 41 shows the methods for personnel to follow when determining the proper way to handle damaged or defective charge storage devices.

This is a classification methodology because Li-ion batteries are currently hazard classified as Class 9 (Miscellaneous hazardous materials)[46] but, when damaged or defective, can present hazards inherent to other hazard classes. For instance,

1. If a battery ruptures, it can present HD 1.2 explosive projection hazards;
2. If a battery experiences overpressure, it presents Class 2 hazards;
3. Overheating presents Class 4 hazards;
4. Leaking effluents present both Class 3 and Class 8 hazards; and
5. Outgassing presents Class 6 hazards.

Coupled with this is that U.S. and international regulations only identify segregation and compatibility requirements for transport of substances and articles hazard classified in Classes 1 through 8. Hence, Li-ion batteries and other high capacity charge storage devices hazard classified as Class 9 are not covered.

As a result of these factors, it is important that the hazards that are most likely to be encountered are properly identified via the recommended classification protocol and suspect devices “classified” in order to properly isolate damaged and defective charge storage devices from other hazardous materials to which the hazards could propagate. None of the containment devices tested nor any of the ones researched by the team possess features capable of mitigating all of the hazards identified from a defective or damaged charge storage device. As such, proper classification is also important when limited containment options are available.

The testing in this study was performed to empirically prove portions of the proposed classification method and to validate and verify the viability of proposed packaging solutions to better ensure safe transport of damaged or defective charge storage devices.

[46] As reflected in 49 CFR 172.101

Figure 42 and Figure 43 show a protocol that was developed by Lithium Fire Guard (formerly PlaneGard). It includes references to the process to be followed for assessing hazards and identifying the proper mitigations action to take, which are the primary purposes of the protocol, and also includes the method for safing a defective or damaged Li-ion battery and associated equipment using their container. It is provided here as a reference only since it is similar to protocols implemented by some airlines and the Missile Defense Agency (MDA) for dealing with damaged and defective charge storage devices.

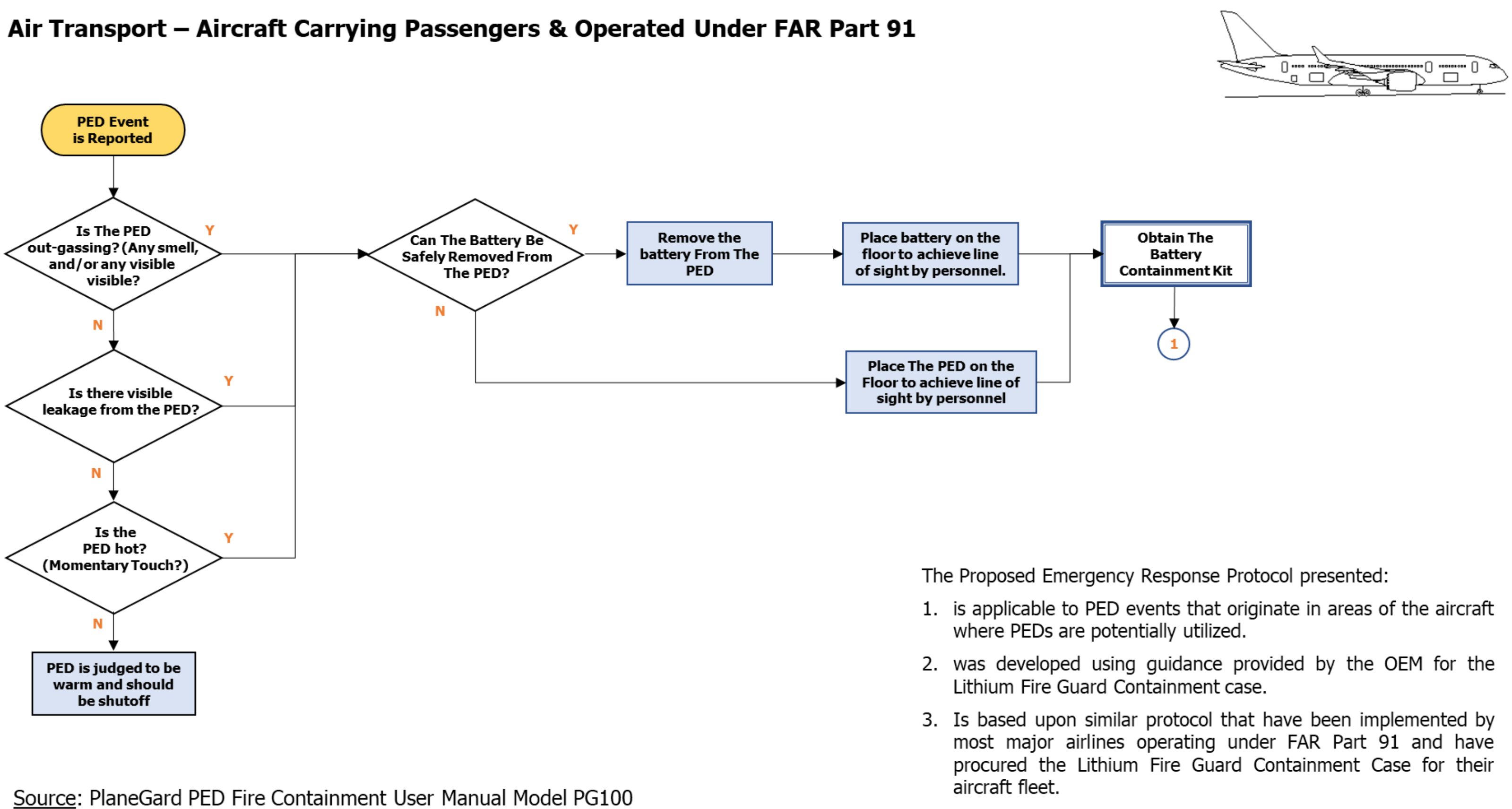
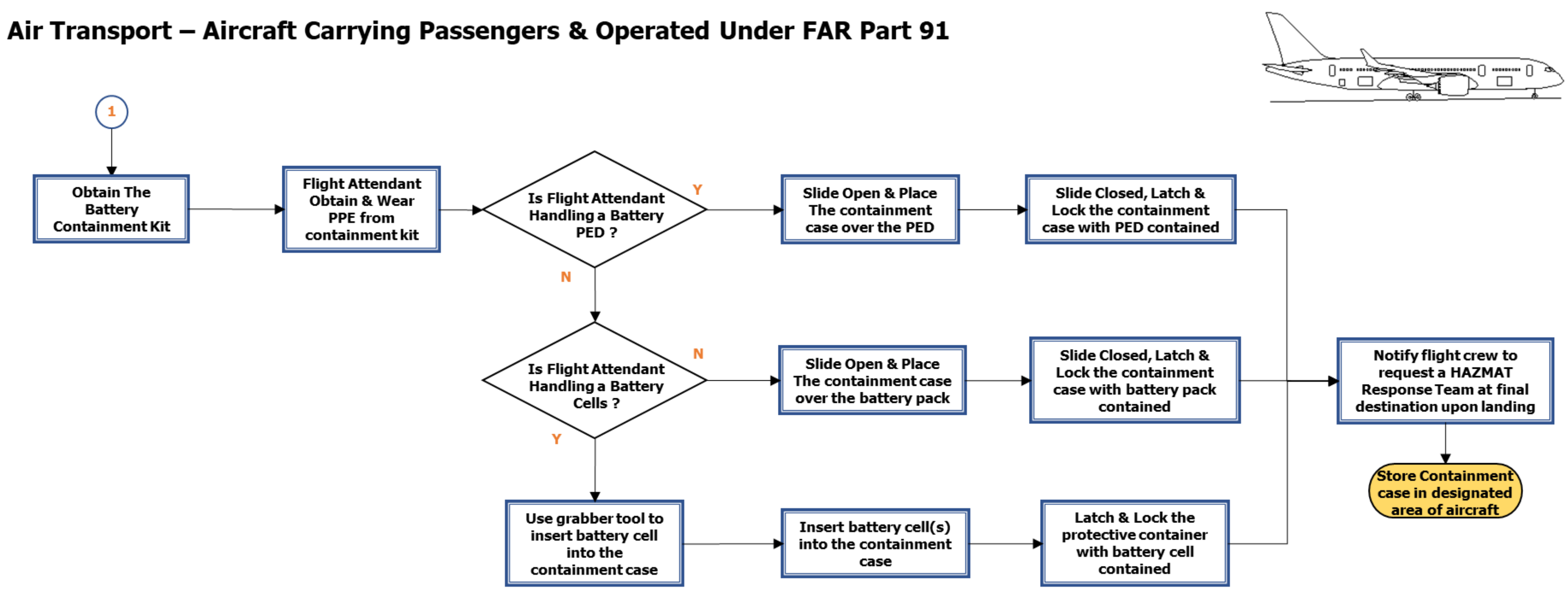


Figure 42: Part 1 of a Li-Ion Battery Safing Protocol for Air Transport in the Passenger Compartment of an Aircraft Operated Under FAR Part 91 Using PlaneGard PED Fire Containment Model PG100



Source: PlaneGard PED Fire Containment User Manual Model PG100

Figure 43: Part 2 of a Li-Ion Battery Safing Protocol for Air Transport in the Passenger Compartment of an Aircraft Operated Under FAR Part 91 Using PlaneGard PED Fire Containment Model PG100

12.0 Recommended Test Methods

One of the primary findings/conclusions from this effort is that safe transport of charge storage devices that become damaged or defective in transit is predicated upon three elements:

1. Proper classification of the devices following an established classification protocol, presented in Section 11.1;
2. Proper handling and packaging of the devices using an appropriate classification methodology, presented in Sections 11.2; and
3. Equipment designed to effectively control the hazards of a damaged or defective charge storage device.

To achieve the third element of this safety support structure, a method to determine the ability of containment equipment to effectively mitigate or ameliorate hazards from defective or damaged charge storage devices is needed. Developing that method was the primary focus of the testing chosen and performed in this study since testing is one of the best ways to verify a safety control's effectiveness.

Since the focus of this study was on evaluating the efficacy of containment to control battery hazards, the tests were chosen based primarily on their capacity to evaluate a container's ability to meet the requirements in Section 7.1.1, which were derived from the PHL and PHA. Additionally, the tests were chosen based on the premise that they should be relatively common, simple, and inexpensive to perform. Otherwise, industry will likely resist their adoption as standard practice.

As such, the four tests described in Section 7.1.3 are recommended for inclusion in a standard test method to establish the effectiveness of a container designed for transport of damaged or defective high capacity charge storage devices. The tests are recommended for inclusion as described in Sections 7.1.3 and 7.3, with the following modifications and exceptions.

Altitude Test

As stated in Section 7.3.1, altitude testing was performed in accordance with Section 38.3.4.1, Test T.1 – Altitude simulation from the *UN Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria*. However, evaluation criteria for that test do not specify a method to determine whether leakage or venting of effluents occurs. As such, a method needs to be implemented to evaluate whether the container is damaged to the point where effluents can escape.

In this study, the team opted to use the combination of an exterior water spray and water indicating paper internal to the container to identify whether a path existed post-test for moisture to enter a container, which could also potentially indicate a path for effluents to escape.

With advancements in the ability to accurately and economically monitor for Li-ion off-gassing, it is recommended that consideration be made to incorporate a requirement that this test be performed with a defective/damaged Li-ion battery simulant placed in the container, such as one used for monitor calibration, and continuous monitoring for Li-ion off-gassing be incorporated throughout the test. This will provide real-time feedback to testers if a breech in the container occurs.

Vibration Testing

No changes are recommended from the test method performed.

Drop Test

As stated in Section 7.3.3, MIL-STD-810G, *Environmental Engineering Considerations and Laboratory Tests* was used as a standard for the drop test. However, evaluation criteria for the Transit Drop Test included in that standard are general and do not specify a method to determine whether leakage or venting of effluents occurs. As such, a method needs to be implemented to evaluate whether the container is damaged to the point where effluents can escape.

In this study, the team opted to use the combination of an exterior water spray and water indicating paper internal to the container to identify whether a path existed post-test for moisture to enter a container, which could also potentially indicate a path for effluents to escape.

With advancements in the ability to accurately and economically monitor for Li-ion off-gassing it is recommended that consideration be made to incorporate a requirement that this test be performed with a defective/damaged Li-ion battery simulant placed in the container, like one used for monitor calibration, and continuous monitoring for Li-ion off-gassing be incorporated throughout the test. This will provide real-time feedback to testers if a breech in the container occurs.

In addition, the simulant should be supplemented by a mass simulator to represent the weight of the heaviest battery for which the container is designed.

Thermal Testing

No changes are recommended from the test method performed.

13.0 Recommended Packaging Standard

Per the SOW for this effort, after completing testing, the APT/SMS Team developed a recommended packaging standard for defective or damaged Li-ion batteries encountered in transit, incorporating the recommended classification protocol and methods, and test methods. The recommended standard provides an itemization of features that should be included in whatever containers chosen for use by industry.

The recommended packaging standards were developed based on the following:

- Research performed during the initial phase of this project
- Preliminary Hazards List (PHL)
- Preliminary Hazards Analysis (PHA)
- Commercially available products
- Testing

These activities are listed in the order in which they were performed.

Results from the research effort were used to produce a list of packaging characteristics that should be incorporated for safe transport of a defective or damaged charge storage device. These characteristics were then expanded in the PHL and PHA to determine whether any inherent hazards or problems are associated with the proposed characteristics. Possible effects, safeguards, and recommendations were generated during this activity.

With the characteristics further refined by the PHL and PHA, a search of commercially available products was performed to identify existing containers that most closely integrate the characteristics identified. Discussions with vendors were part of this activity and these inputs were considered when refining recommended packaging characteristics.

Commercially available products were procured and subjected to testing. The results were evaluated primarily to verify that the recommended testing methods provide insight into a container's ability to mitigate hazards by incorporating recommended packaging characteristics. The results of these tests were also used to evaluate the commercially available products as a baseline.

In developing a list of packaging characteristics, a general list was the focus rather than any specific commercial product or feature. The intent of the project was to evaluate the options available and develop a composite list of specifications, not to endorse a specific company's product.

The list of packaging characteristics recommended for inclusion in a packaging standard for defective or damaged charge storage device containers has been presented multiple times in this report since they were used as the test requirements against which container performance was measured. These included:

1. Ability to contain effluents (defined in Section 38.3.2.2 of the *UN Manual of Tests and Criteria* to be a liquid or gas)
2. Ability to contain fire
3. Ability to contain fragments
4. Surfaces of the container should not reach levels that could burn personnel
5. Release of hazardous or corrosive material from the battery should be contained

6. Batteries should be secure in the container and not loose where they may contact container interior surfaces
7. If multiple batteries are contained, verification is required that an event from one battery will not propagate to an adjacent battery
8. Protect the battery from external contamination that could initiate or exacerbate a thermal reaction
9. The container materials of construction should be compatible with the battery, ensuring that a leak will not result in a subsequent reaction between the battery fluid and the container materials

As noted earlier, none of the containers tested could control all hazards. Control of all hazards could potentially be accomplished by placing one container inside another of a dissimilar design. However, this would require personnel to handle the suspect devices longer and, if the containers are not designed for use together, could introduce unforeseen secondary hazards.

13.1 OUTLINED CONTENTS OF STANDARD

The following specific packaging features have been identified to accomplish the nine packaging characteristics listed in Section 13.0 for transportation of defective or damaged batteries encountered during transport.

- Container-in-container design
- Non-metallic inner packaging
- Non-conductive, non-flammable, absorbent cushioning material
- Labeling in accordance with DOT and UN international requirements
- Materials compatible with batteries and associated hazardous materials
- Unless specifically designed to accommodate separation and isolation of multiple batteries, only one battery should be placed in a container

The container-in-container design is recommended since it provides protection against leaks that may occur. In addition, if there is a thermal event in the battery, the inner and outer containers, as well as the inner packing, will help dissipate the heat, thereby keeping outer packaging surface temperatures lower.

Non-metallic packaging will help mitigate short circuit hazards. Short circuits can lead to fires and injuries to personnel.

It is recommended that non-conductive, non-flammable, absorbent cushioning material be used between the outer and inner packages. The material should surround the battery in the inner packaging and the inner package itself. As described with the container-in-container design above, this safeguard protects against thermal events and leaks that may occur during transport of defective or damaged charge storage devices. This also ensures that the batteries are protected from additional damage caused by movements of the inner packaging.

Existing DOT and UN international requirements should be followed at all times, including labeling. Appropriate labeling ensures that personnel who are handling the packaging are aware that there is a defective or damaged charge storage device in the package. This will help protect personnel from hazards that they may otherwise become exposed to during handling operations.

Materials should be compatible with the battery and its hazardous material. Incompatible material contact with the battery, battery components, battery materials, or associated items may cause exacerbation of incidents that may occur. Potential incidents include thermal deviations, explosions, and adverse chemical reactions.

Unless specifically designed to accommodate separation and isolation of multiple batteries, only one battery should be placed in a container. If multiple batteries are placed in a single container, hazards caused by one battery interacting with another, such as short circuits, could occur and contribute to an incident.

13.2 INFORMATION POPULATED INTO 49 CFR § 172.101 FORMAT

Using the information and recommendations outlined in Section 13.1, several updates to the existing 49 CFR regulations are proposed. Table 15 shows excerpts from the Hazardous Materials Table in 49 CFR § 172.101 that are applicable to Li-ion battery transport. The recommended additions are included as items (5) through (11) after the 49 CFR § 172.101 excerpts, using the numbering scheme in 49 CFR § 173.185.

Table 15: Recommended Changes to 49 CFR § 172.101 Hazardous Materials Table for Lithium Ion Batteries

Symbols (1)	**Hazardous material descriptions and proper shipping names (2)**	**Hazard class or Division (3)**	**Identification Numbers (4)**	**PG (5)**	**Label Codes (6)**	**Special Provisions (172.102) (7)**	**(8)** Packaging (§173.***)			**(9)** Quantity Limitations (see §§173.27 and 175.75)		**(10)** Vessel Stowage	
							Exceptions (8A)	Non-bulk (8B)	Bulk (8C)	Passenger Aircraft (rail) (9A)	Cargo Aircraft Only (9B)	Location (10A)	Other (10B)
	Lithium ion batteries including lithium ion polymer batteries	9	UN3480	….	9	388, 422, A54, A100	185	185	185	Forbidden	35 kg	A	
	Lithium ion batteries contained in equipment including lithium ion polymer batteries	9	UN3481	….	9	181, 388, 422, A54	185	185	185	5 kg	35 kg	A	
	Lithium ion batteries packed with equipment including lithium ion polymer batteries	9	UN3481	….	9	181, 388, 422, A54	185	185	185	5 kg	35 kg	A	
	Lithium metal batteries including lithium alloy batteries	9	UN3090	….	9	388, 422, A54	185	185	185	Forbidden	35 kg	A	
	Lithium metal batteries contained in	9	UN3091	….	9	181, 388, 422, A54, A101	185	185	185	5 kg	35 kg	A	

Symbols (1)	Hazardous material descriptions and proper shipping names (2)	Hazard class or Division (3)	Identification Numbers (4)	PG (5)	Label Codes (6)	Special Provisions (172.102) (7)	(8) Packaging (§173.***)			(9) Quantity Limitations (see §§173.27 and 175.75)		(10) Vessel Stowage	
							Exceptions (8A)	Non-bulk (8B)	Bulk (8C)	Passenger Aircraft (rail) (9A)	Cargo Aircraft Only (9B)	Location (10A)	Other (10B)
	equipment including lithium alloy batteries												
	Lithium metal batteries packed with equipment including lithium alloy batteries	9	UN3091	….	9	181, 388, 422, A54	185	185	185	5 kg	35 kg	A	

The various special provisions in Column 7 from the §172.101 table are defined below.

181. When a package contains a combination of lithium batteries contained in equipment and lithium batteries packed with equipment, the following requirements apply: a. The shipper must ensure that all applicable requirements of §173.185 of this subchapter are met. The total mass of lithium batteries contained in any package must not exceed the quantity limits in columns (9A) and (9B) for passenger aircraft or cargo aircraft, as applicable; b. Except as provided in §173.185(c)(3) of this subchapter, the package must be marked "UN 3091 Lithium metal batteries packed with equipment," or "UN 3481 Lithium ion batteries packed with equipment," as appropriate. If a package contains both lithium metal batteries and lithium ion batteries packed with and contained in equipment, the package must be marked as required for both battery types. However, button cell batteries installed in equipment (including circuit boards) need not be considered; and c. The shipping paper must indicate "UN 3091 Lithium metal batteries packed with equipment" or "UN 3481 Lithium ion batteries packed with equipment," as appropriate. If a package contains both lithium metal batteries and lithium ion batteries packed with and contained in equipment, then the shipping paper must indicate both "UN 3091 Lithium metal batteries packed with equipment" and "UN 3481 Lithium ion batteries packed with equipment."

388. a. Lithium batteries containing both primary lithium metal cells and rechargeable lithium ion cells that are not designed to be externally charged, must meet the following conditions:

i. The rechargeable lithium ion cells can only be charged from the primary lithium metal cells;

ii. Overcharge of the rechargeable lithium ion cells is precluded by design;

iii. The battery has been tested as a primary lithium battery; and

iv. Component cells of the battery must be of a type proved to meet the respective testing requirements of the Manual of Tests and Criteria, part III, subsection 38.3 (IBR, see §171.7 of this subchapter).

b. Lithium batteries conforming to paragraph a. of this special provision must be assigned to UN Nos. 3090 or 3091, as appropriate. When such batteries are transported in accordance with §173.185(c), the total lithium content of all lithium metal cells contained in the battery must not exceed 1.5 g and the total capacity of all lithium ion cells contained in the battery must not exceed 10 Wh.

422. When labelling is required, the label to be used must be the label shown in §172.447. Labels conforming to requirements in place on December 31, 2016 may continue to be used until December 31, 2018. When a placard is displayed, the placard must be the placard shown in §172.560.

A54. Irrespective of the quantity limits in Column 9B of the §172.101 table, a lithium battery, including a lithium battery packed with, or contained in, equipment that otherwise meets the applicable requirements of §173.185, may have a mass exceeding 35 kg if approved by the Associate Administrator prior to shipment.

A100. Lithium ion cells and batteries must be offered for transport at a state of charge not exceeding 30 percent of their rated capacity. Lithium ion cells and batteries at a state of charge greater than 30 percent of their rated capacity may only be transported under conditions approved by the Associate Administrator in accordance with the requirements in 49 CFR part 107, subpart H. Guidance and methodology for determining the rated capacity can be found in sub-section 38.3.2.3 of the UN Manual of Tests and Criteria (IBR, see §171.7 of this subchapter).

A101. In addition to the applicable requirements of §173.185, the quantity of lithium metal in the batteries contained in any piece of equipment must not exceed 12 g per cell and 500 g per battery.

In addition to these special provisions, packaging references are in place to 49 CFR 173.185. In 49 CFR 173.185, subpart f, the following explanation and requirements are set forth for damaged, defective, or recalled batteries:

(f) Damaged, defective, or recalled cells or batteries. Lithium cells or batteries, that have been damaged or identified by the manufacturer as being defective for safety reasons, that have the potential of producing a dangerous evolution of heat, fire, or short circuit (e.g., those being returned to the manufacturer for safety reasons) may be transported by highway, rail or vessel only, and must be packaged as follows: (1) Each cell or battery must be placed in individual, non-metallic inner packaging that completely encloses the cell or battery; (2) The inner packaging must be surrounded by cushioning material that is non-combustible, non-conductive, and absorbent; and (3) Each inner packaging must be individually placed in one of the following packagings meeting the applicable requirements of part 178, subparts L, M, P and Q of this subchapter at the Packing Group I level: (i) Metal (4A, 4B, 4N), wooden (4C1, 4C2, 4D, 4F), or solid plastic (4H2) box; (ii) Metal (1A2, 1B2, 1N2), plywood (1D), or plastic (1H2) drum; or (iii) For a single battery or for a single battery contained in equipment, the following rigid large packagings are authorized: (A) Metal (50A, 50B, 50N); (B) Rigid plastic (50H); (C) Plywood (50D); and (4) The outer package must be marked with an indication that the package contains a “Damaged/defective lithium ion battery” and/or “Damaged/defective lithium metal battery” as appropriate. The marking required by this paragraph (f)(4) must be in characters at least 12 mm (0.47 inches) high.

Based on the current requirements in 49 CFR § 172.101 and 49 CFR § 173.185, as well as the provisions identified in Section 14.0, it is proposed that the following updates be made to the requirements in 49 CFR § 173.185.

(5) Container-in-container design should be incorporated as part of containers designed for transportation of damaged, defective, or recalled cells or batteries.

(6) All container materials should be compatible with the battery, potential battery effluents, and all other hazardous materials associated with the battery.

(7) Only one damaged, defective, or recalled battery should be placed in an inner container unless the container is specifically designed to contain more than one battery, with separation and isolation capabilities incorporated.

(8) The container-in-container design should ensure that a thermal event or deviation in the inner packaging will be contained and the exterior surfaces of the outer packaging will remain at a safe temperature for handling by personnel.

(9) The container-in-container configuration should be designed to withstand and minimize the effects of fragmentation.

(10) Means should be in place to ensure that the battery in the inner packaging is kept securely in place. This may be accomplished through appropriate support of the inner container by the packing material between the inner and outer containers.

(11) The container-in-container configuration should be designed to contain materials within the inner packaging such as leaks or outgassing of effluents that may result from a damaged or defective battery.

14.0 Hazard-Specific Container Recommendations to Achieve Mitigation/Control of Hazards during Transport

Based on the testing performed, the PHL, the PHA, and commercially available products, several container characteristics have been identified that will maximize the probability of safe transport when damaged or defective Li-ion batteries are encountered in transit. Table 16 presents a summary of these recommendations organized by predominant hazards. The recommendations in the table are expanded upon in the section that follows.

Table 16: Container Design Recommendations

Potential Hazard	Container Recommendation
Outgassing	• Provide containers that are equipped with optional venting, in both the inner container and the outer container.
Fire	• Provide containers that provide protection against thermal stimulus. For example, the inner packing material may be specifically designed to absorb heat from the inner container.
Heat	• Provide a container-in-container design to allow dissipation of heat. • Provide containers that provide protection against thermal stimulus. For example, the inner packing material may be specifically designed to absorb heat from the inner container.
Health hazards (corrosion or toxicity)	• Provide leak-absorbent material in the inner space between the inner and outer packaging. • Detail proper PPE that personnel should have when handling damaged Li-ion batteries.*

Potential Hazard	Container Recommendation
Fragmentation	• Ensure all packaging complies with appropriate 49 CFR Part 178, UN or European specifications (e.g., 5.5L UN1A2 drum, UN rated 5G/Y6.3 box, etc.). The materials of construction should be specified to withstand and minimize the effects of fragmentation (e.g., aluminum, steel, etc.).
Thermal runaway	• To prevent thermal runaway from progressing: – Provide a container-in-container design to allow dissipation of heat. – Provide containers that provide protection against thermal stimulus. For example, the inner packing material may be specifically designed to absorb heat from the inner container. – Incorporate a cooling system • Provide criteria to screen batteries for potential hazards such as aging, electronic protection failures, etc.*
Impact	• Batteries are to be kept secure in the packaging. The inner container should be supported with appropriate packing material. • Provide warnings/cautions to remove potential foreign objects from the area of battery cells or ensure that they are positively secure.*
Propagation	• Only one battery or battery pack should be placed in each container unless a positive means for physical separation/isolation exists
Contamination	• Packaging should ensure a tight seal and that moisture is not allowed in or out.
Compatibility	• Containers should be designed, and materials chosen, with consideration of their compatibility with different types of charge storage device electrolytes and components. • Manufacturers should include a label identifying compatible or incompatible charge storage devices.
Short circuit	• Only one battery or battery pack should be placed in each container unless adequate separation/isolation between devices can be accomplished.

*These recommendations are not packaging related.

Containers for defective or damaged charge storage devices encountered in transit should be equipped with a sealed container-in-container design. This provides protection against leaks and can prevent injury or propagation from thermal heating from occurring. Thermal hazards should also be addressed by designing the inner packing material to be heat absorbent and made from non-conductive, non-metallic materials to prevent short circuits. Propagation risks from short circuiting can also be mitigated by placing only one battery in a container unless the container is specifically designed to contain more than one battery, with separation and isolation capabilities incorporated in it. Thermal hazards should also be mitigated by ensuring that a container's construction materials are compatible with battery materials and effluents, as well as hazardous materials associated with battery failure.

In addition to using a sealed container, leakage can also be mitigated by using leak absorbent material in the inner space between the inner and outer packaging and by using containers designed and qualified by test for vibration, impact, and protection from external energy stimulus. This will additionally reduce the potential for package fragmentation. All containers should comply with existing governing regulations, including UN or European specifications.

The containers should be designed to ensure a tight seal can be established so moisture is not allowed pass in or out. This will further reduce hazards associated with battery effluents (liquid or gas) and associated byproducts.

To minimize pressurization and associated rupture, it is recommended that optional venting be incorporated in both the inner and outer container. Venting should be optional since, although desirable for limiting overpressure, the ability to seal the container is needed in the event of outgassing or excessive moisture that could react with leaking electrolyte. Protection of the batteries themselves from vibration, movement, external stimulus, and similar hazards can be achieved by securing the inner packaging with appropriate packing material.

15.0 Non-Containment Mitigations and Controls

As mentioned previously, a major focus of this study was to identify whether containment solutions alone are capable of mitigating or ameliorating all of the hazards associated with defective or damaged charge storage devices encountered in transit. None of the containment devices tested in this study demonstrated the ability to sufficiently meet all nine test requirements against which container performance was measured. However, with some minor modifications, it should be possible for some of the tested containers to meet all nine test requirements and thereby be able to adequately control hazards identified from defective or damaged Li-ion batteries and other charge storage devices in some transportation modes and configurations.

However, one of the findings of this study was that containment is not a reasonable solution for some configurations and transportation modes. Examples include bulk transport of batteries on a pallet or a battery installed in a large device that will not fit in a container. Extra-large, pallet-sized containment bags and bins currently exist on the market.

In the case of a pallet of batteries, failure of one battery propagating to others on the pallet can quickly become a runaway event with higher temperatures and more dynamic reactions than would be expected from a single cell. Containment bags are designed to maintain their structural integrity at high temperatures for a certain amount of time. If the length of a flight in a cargo plane exceeded that containment period, the results could be catastrophic.

Likewise, in the case of a large device that has a defective or damaged charge storage device integrated into its design, unless an extra-large container is maintained on hand, containment is not an option.

Another major aspect of each of the container solutions provided in this study is the ability to detect a device that begins to exhibit signs of being defective or damaged in transit. This is not likely in most modes of transportation for commerce where the devices will be in a rail car, trailer, on-board container or cargo hold.

As such, a major recommendation from this study is that, in addition to standards and guidance being developed for containment solutions, similar research should be conducted into detection and suppression technology for Li-ion and other charge storage devices.

The draft protocols in Figure 44 through Figure 47 assume implementation of a detection system with remote monitoring capability to warn personnel of smoke or outgassing from damaged or defective Li-ion batteries and a fire or smoke suppression system. For over the road or rail transport, response by personnel would require the vehicle to be stopped.

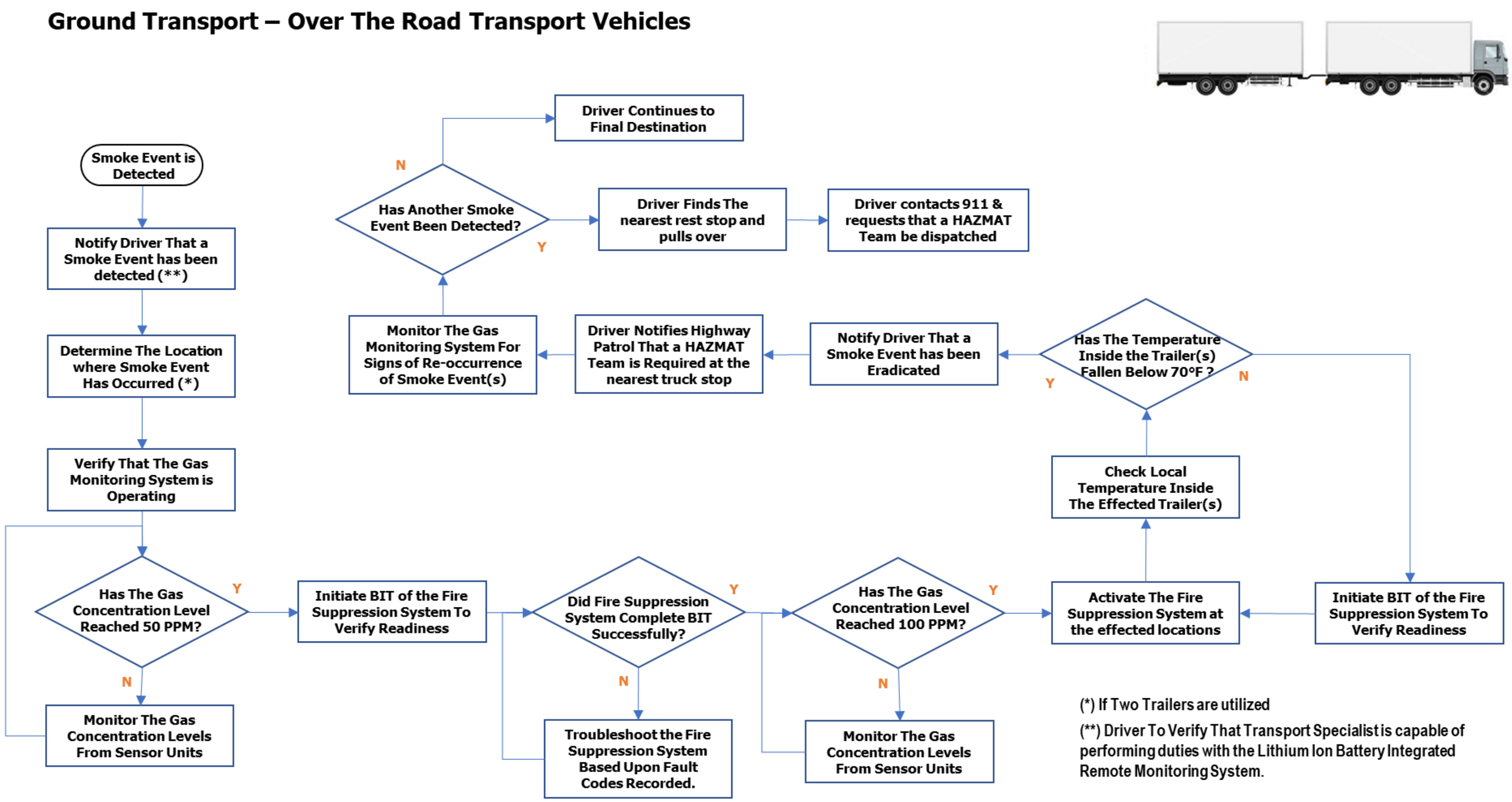


Figure 44: Recommended Li-Ion Battery Safing Protocol for Over the Road Transport

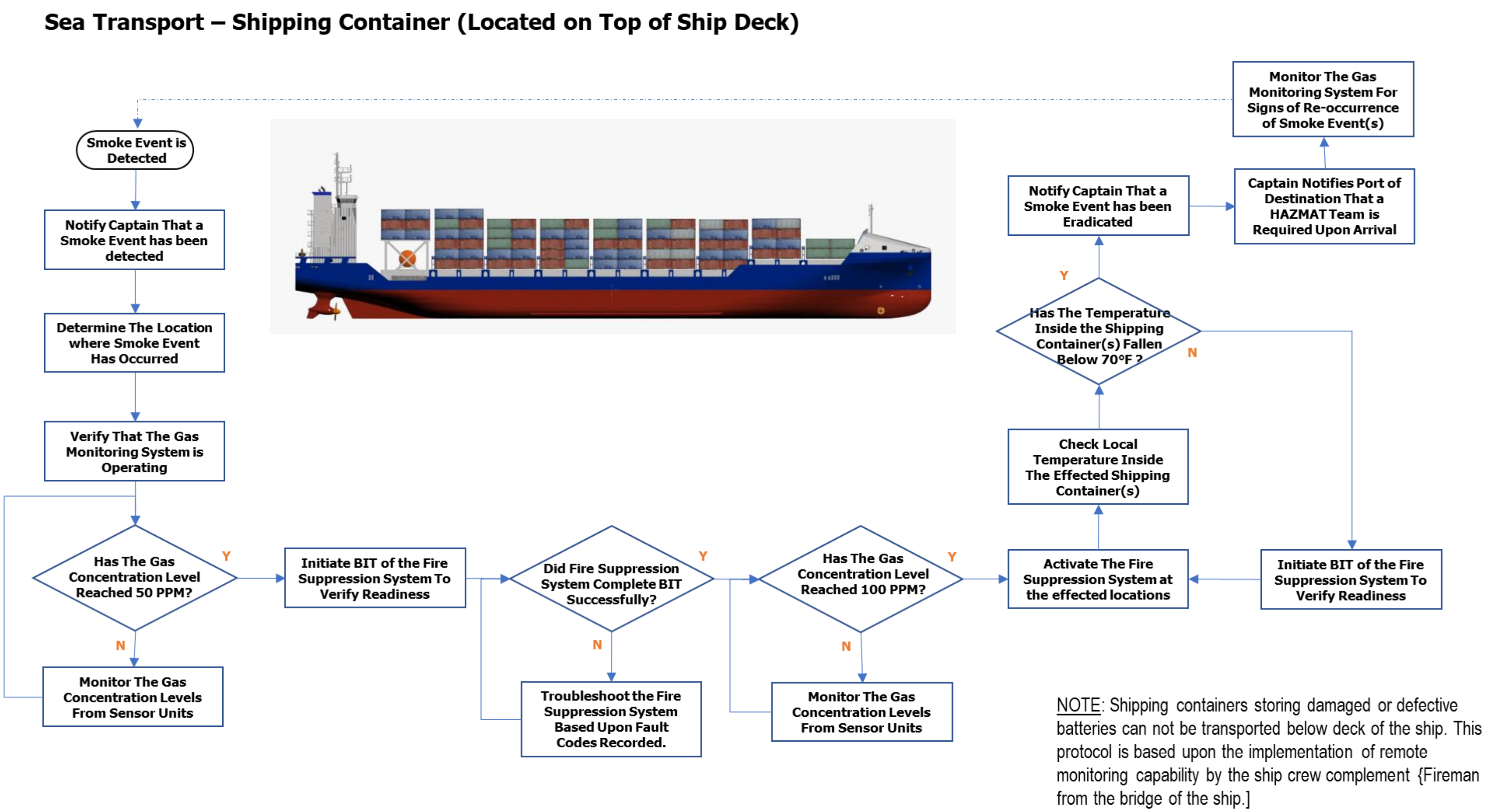


Figure 45: Recommended Li-Ion Battery Safing Protocol for Sea Transport in a Shipping Container

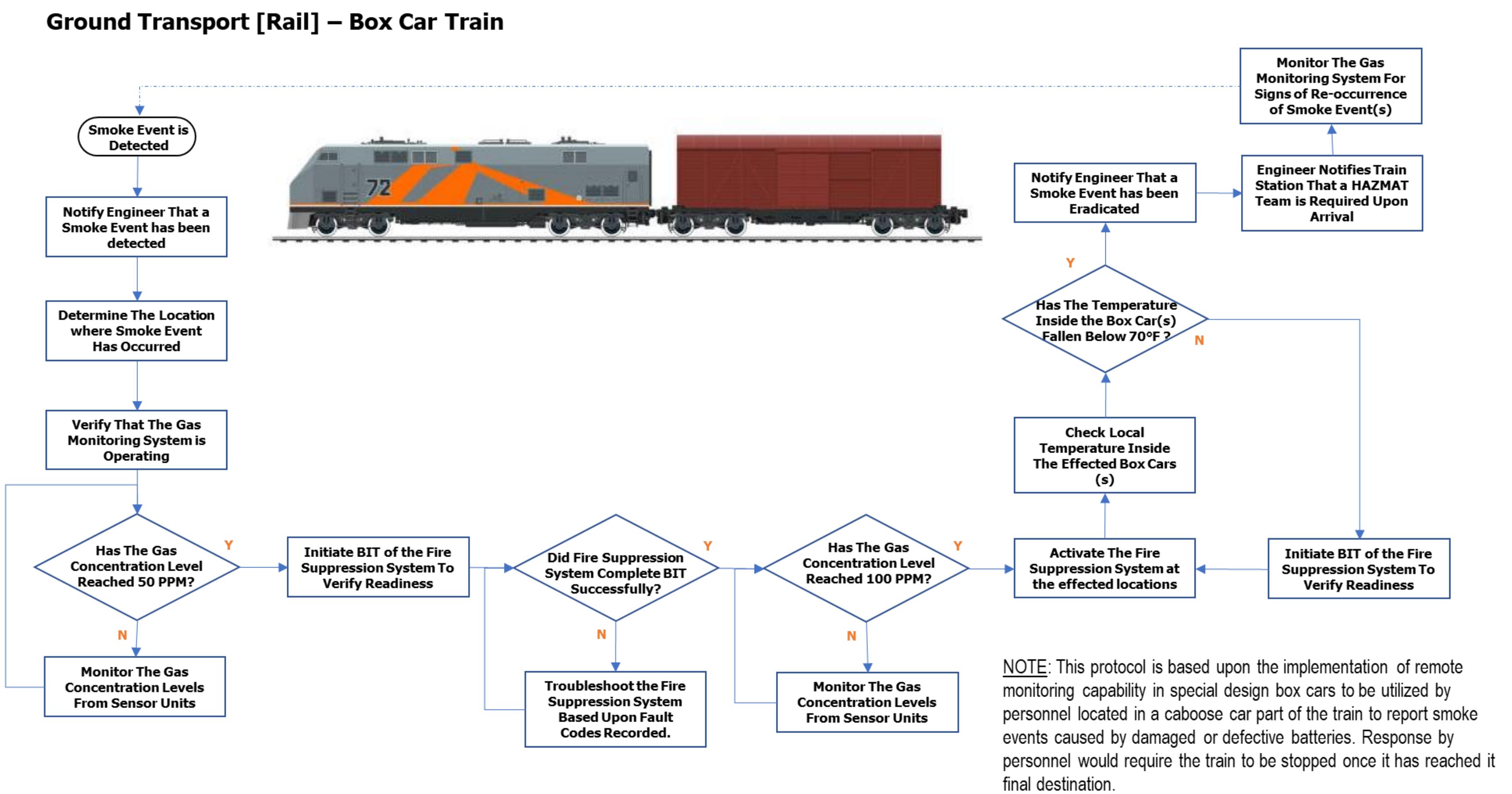


Figure 46: Recommended Li-Ion Battery Safing Protocol for Ground Transport by Rail in a Box Car

Air Transport – Cargo Hold of a Passenger Aircraft or on a Cargo Aircraft

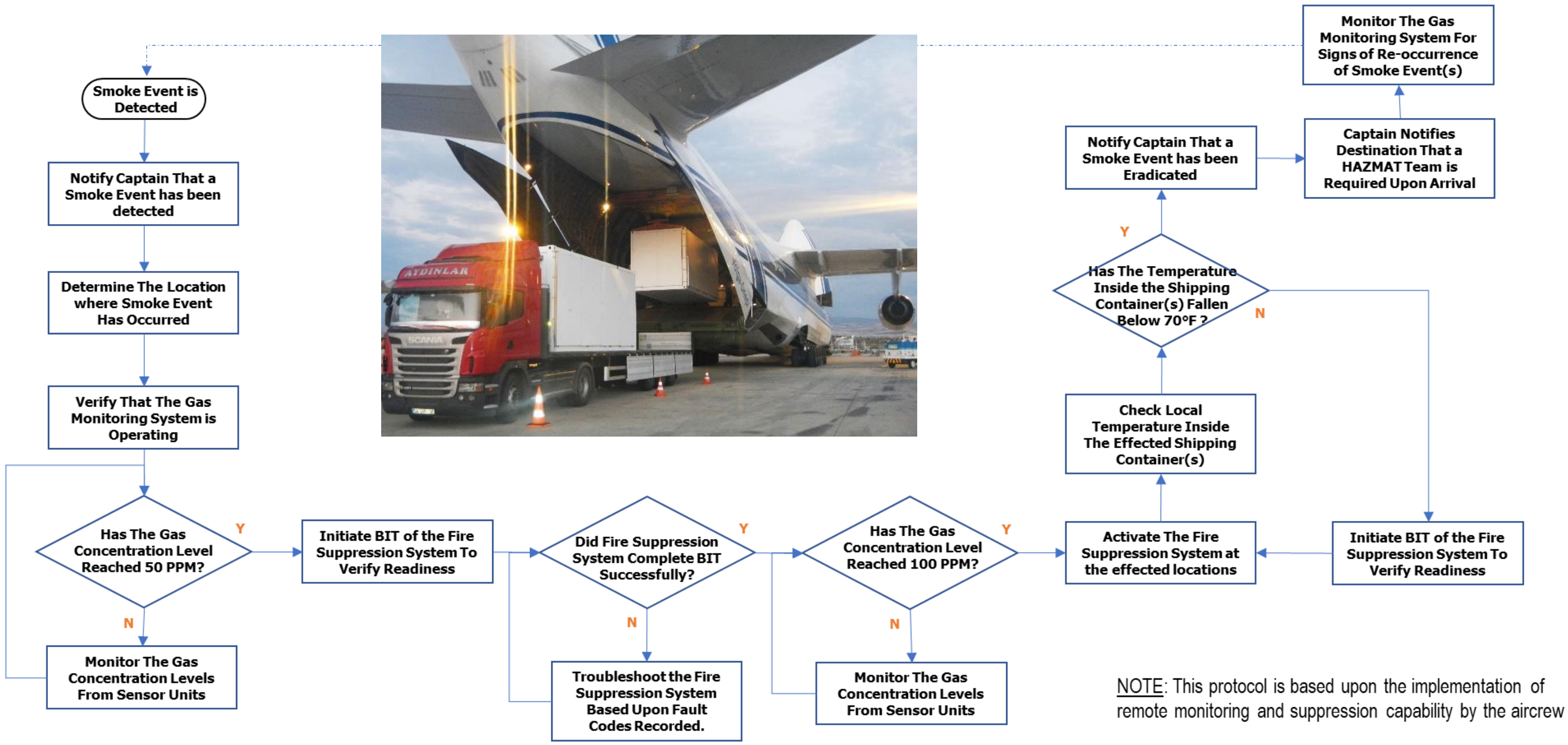


Figure 47: Recommended Li-Ion Battery Safing Protocol for Air Transport in Cargo Hold of a Passenger Aircraft or on a Cargo Aircraft

15.1 RECOMMENDED METHODS FOR SAFE TRANSPORT

Based on the hazards identified in the PHL and PHA, and the draft classification protocols, classification methods have been developed. As previously explained, these classification methods are intended to be simple procedures using dedicated equipment that can be used to safely mitigate or ameliorate the realization of hazards from a defective or damaged Li-ion battery during transport. Based on the team's findings, these methods are expected to fall into one of two categories: containment or detection.

Many of the draft protocols shown in the previous figures include references to draft safing methods. In addition, Figure 48 and Figure 49 show some notional concepts for using detectors in transport.

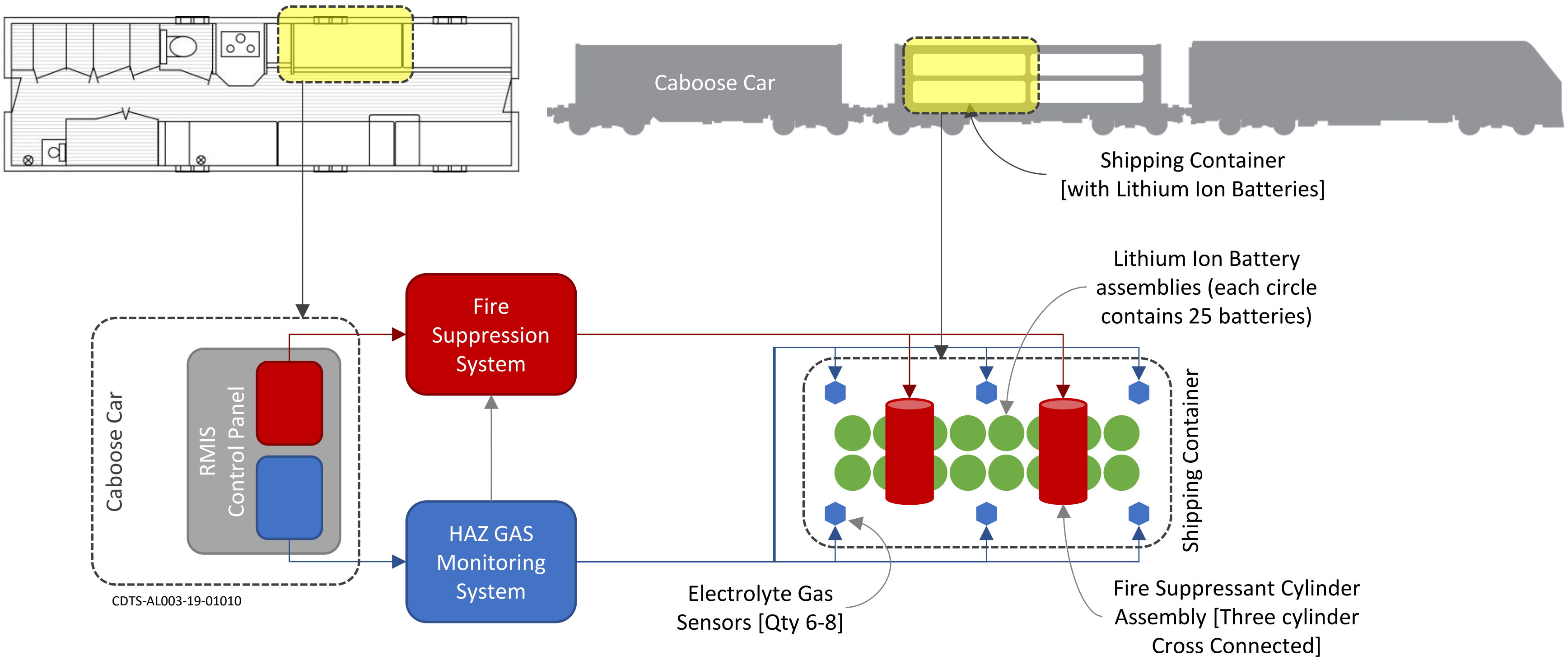


Figure 48: Lithium Ion Battery Remote Monitoring Integrated System (RMIS) Notional Concept – Ground [Rail] Transport

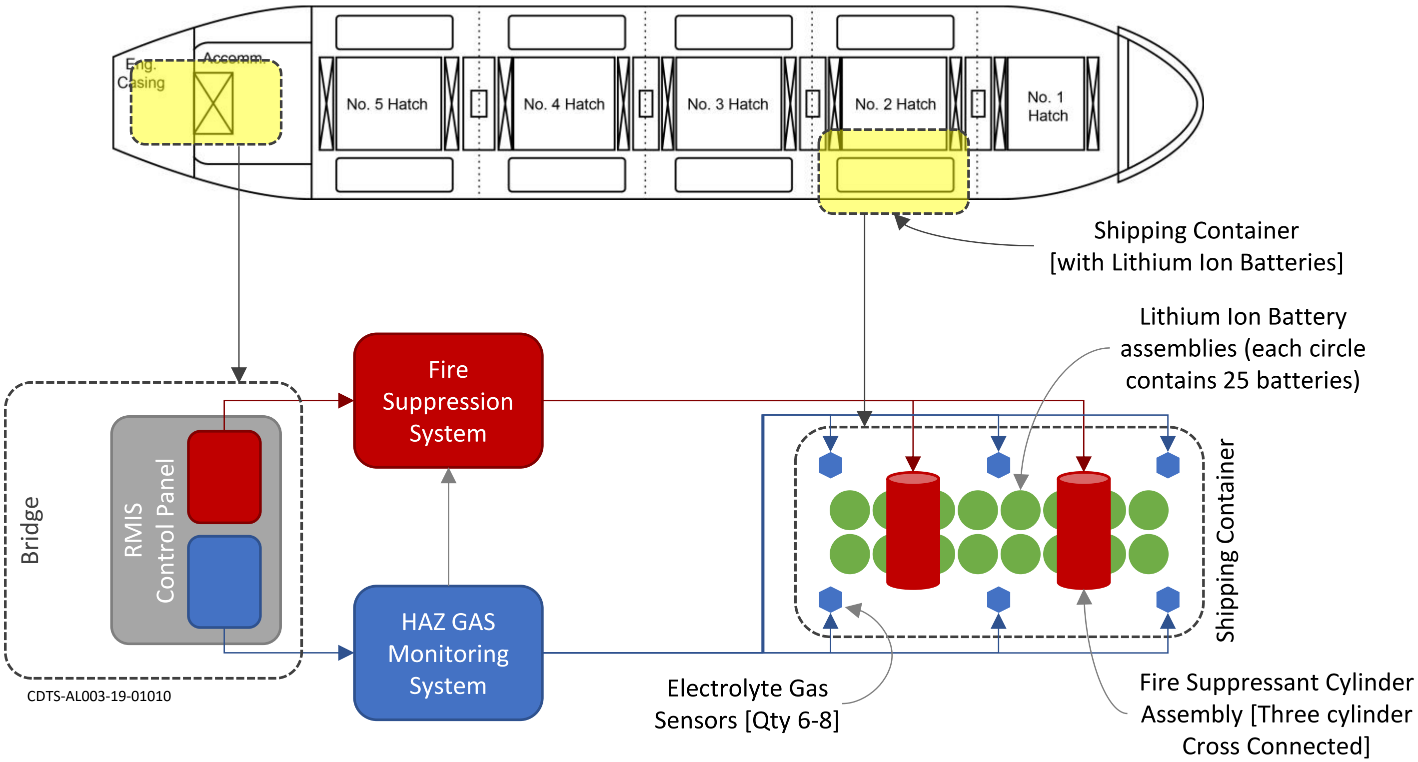


Figure 49: Lithium Ion Battery Remote Monitoring Integrated System (RMIS) Notional Concept – Sea Transport

PART V: PATH FORWARD

To integrate the findings and recommendations of this study into a safe, reliable, and effective packaging standard that will be accepted by industry and regulators, the next steps should include research into a packaging system that incorporates a detection system and suppression system. The packaging configuration should have a detection system that remotely notifies an operator that on-board batteries have been detected entering thermal runaway. This should then either automatically initiate a suppression system or provide an option for an operator to initiate one to extinguish an event. This would prevent the spread of a thermal runaway event to other Li-ion batteries or other hazardous materials that may be proximal to the damaged or defective device, thus mitigating further damage to the transport vehicle. An automated system would remove response personnel from the immediate danger of the identified hazard of a thermal runaway event.

In addition, as previously discussed in Section 13.2 and other sections in this report, high capacity charge storage devices, including Li-ion batteries, are currently hazard classified as Class 9 (Miscellaneous hazardous materials). U.S. and international regulations only identify segregation and compatibility requirements for transport of substances and articles hazard classified in Classes 1 through 8. Hence, high capacity charge storage devices (Class 9) are not covered.

49 CFR § 177.848(e)(1) provides instructions for using the segregation table for HM as follows, “The absence of any hazard class or division or a blank space in the table indicates that no restrictions apply.” Since the table only includes Classes 1–8 and a hazard class or division that is not on listed on the table is not restricted, segregation rules do not apply to Li-ion batteries and other Class 9 substances and materials.

Damaged or defective high capacity charge storage devices can present hazards inherent to other hazard classes, including:

1. HD 1.2 explosive projection hazards if a battery ruptures;
2. Class 2 hazards if a battery experiences overpressure;
3. Class 4 hazards in the event of overheating;
4. Class 3 and Class 8 hazards if leaking effluents are present; and
5. Class 6 hazards from outgassing.

The potential exists that a damaged or defective Li-ion battery or other charge storage device could unknowingly be placed next to an HC 1 or other hazardous material by a commercial transporter. In the event any of the hazards listed above manifest, propagation could create a much bigger and more dangerous situation.

It is therefore recommended that a study be performed to develop proposed regulations regarding transport of Class 1 explosives and other non-Class 9 HM with high capacity charge storage devices, currently classified as Class 9. The intended impact is to reduce the probability that a Li-ion battery failure could initiate a nearby HM during transport, propagating a more serious event.

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Appendix A – Test Plan

A-P-T RESEARCH, INC.
AN EMPLOYEE-OWNED COMPANY

SMS
SAFETY MANAGEMENT SERVICES

DOT PHMSA Project 46 (TA-2) Defective and Damaged Lithium Ion Battery Test Plan

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CDTS-AL003-19-01600

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ATTACHMENTS

Attachment 1:

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1.0 Test Series Description

Testing will be performed to verify the packaging methods identified as potential solutions to effectively ensure the safe transportation of defective or damaged charge storage devices (lithium ion batteries) encountered during transportation.

2.0 Testing Objectives

The primary objectives of the tests will be to verify or disprove the adequacy of the identified potential solutions to control hazards associated to lithium ion batteries based on incident reports and the associated PHL/PHA, namely:

- Battery Cell Electrolyte Leakage
- Outgassing
- Explosion/Fragmentation
- Fire/Heat
- Thermal Runaway
- Electrical Failure
- Health Hazards

3.0 Design of Experiments (DOE)

The team performed a DOE analysis to identify the most efficient method to achieve the primary objectives of the tests. The results of the DOE have then been used to confirm which tests to run, which tests batteries will need to be used and which tests can use a simulator, the configuration of the batteries to provide worst case conditions, and why the test configurations chosen will provide enough data to confidently anchor conclusions from the tests.

TEST ARTICLES:

Table 1 is a listing of the articles identified for potential use in testing.

Table 1. Articles for Test

Item	Quantity	Voltage	Application	Chemistry
Sony, Samsung, LG or Tenergy High Discharge 18650 Batteries	40	3.7	E-Cigs	LiNiMnCoO2, LiCoO or LiMnO2
DJI 4-cell Li-Po Batteries	4	15.4	Drones	LiPo
Apple iPhones	4		Cell phones	LiPo
Samsung Cell Phones	4		Cell phones	LiPo
Dell 6-cell Li-Ion Laptop Batteries	4		Laptop	
Flight Fire Box FXB-7	2	NA		NA
Lithium Fire Guard (formerly Planegard)	2	NA		NA

Item	Quantity	Voltage	Application	Chemistry
CellBlock LIBIK	2	NA		NA

ANALYSIS SUMMARY:

Figure 1 graphically identifies the inputs into the analysis and the variables that were considered.

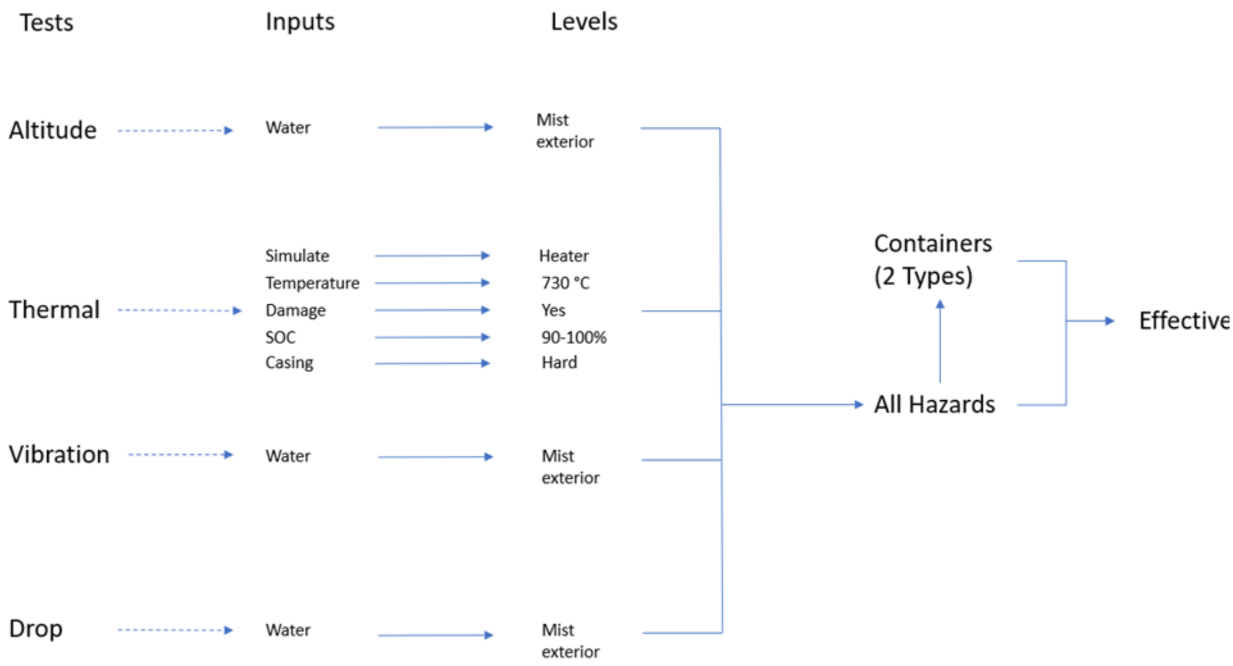

Figure 2. DOE Inputs and Considerations

Batteries. The considerations for the batteries included:

- Types of batteries needed to test worst case conditions against each mitigation and to replicate each identified hazard
- If a battery is needed to achieve test objectives, or a simulant can be used to improve reliability and safety
- Which variables need to be taken into consideration to replicate worst case conditions against which to test the mitigations. These included:
  - Temperature – can affect the efficiency of the battery, potentially producing a slower rate of energy "burnoff" during failure
  - State of Charge (SOC) – the higher the state of charge, the more energy the battery can potentially generate during failure
  - Damage – can affect built-in safety features of the battery that may lead to more hazards, more severe hazards or propagation of hazards
  - Battery casing (hard or soft)

Hazards to replicate. As stated earlier, the primary objective of the tests will be to gauge the effectiveness of a containment unit to protect against the following hazards:

- Battery Cell Electrolyte Leakage
- Outgassing
- Explosion/Fragmentation
- Fire/Heat
- Thermal Runaway
- Electrical Failure
- Health Hazards

Tests. To achieve this, the team began with a list of twelve tests that were potential candidates to be part of the testing protocol. Based on the hazards to be evaluated and the nature of the tests, the list was reduced to four:

- Altitude test – simulates aspects of transport on an airplane.
- Thermal test – simulates aspects of transport with a battery on fire, at high heat, or in thermal runaway.
- Vibration test – simulates environmental aspects during all transportation scenarios.
- Drop test – simulates being dropped from a height.

Performing these four tests will provide the data needed to evaluate the effectiveness of a mitigation. In addition, it is believed that these four tests capture the primary hazards and energy stimuli to which the batteries may be subjected during transportation.

Containers. As a starting point, rather than design a new container, based on the results of the PHL/PHA, the team derived and documented the features needed in a container to control the identified hazards and then researched products already on the market that met that criteria. Three strong candidates were identified, two of which will be used in testing:

- Lithium Fire Guard (formerly PlaneGard)
- CellBlock LIBIK
- Aero PED Fire ConEx (formerly Flight Fire Box FXB-7 – *not available for testing*)

TEST CONFIGURATION RECOMMENDATIONS FROM DOE:

Test	**Materials**	**Hazards Address**
Altitude	PlaneGard, 0 batteries, Water misted over exterior	Leakage, Outgassing, Health
	CellBlock, 0 batteries, Water misted over exterior	Leakage, Outgassing, Health

Thermal	PlaneGard, 0 batteries, Heater placed inside @ 730 °C for 2 minutes	Fire/Heat, Thermal Runaway, Health
	CellBlock, 0 batteries, Heater placed inside @ 730 °C for 2 minutes	Fire/Heat, Thermal Runaway, Health
	PlaneGard, 10 - 18650 batteries, Damaged, 90-100% state of charge, Hard cased batteries	Fire/Heat, Thermal Runaway, Explosion/Frag, Health
	CellBlock, 10 - 18650 batteries, Damaged, 90-100% state of charge, Hard cased batteries	Fire/Heat, Thermal Runaway, Explosion/Frag, Health
Vibration	PlaneGard, 0 batteries, Water misted over exterior	Leakage, Outgassing, Health
	CellBlock, 0 batteries, Water misted over exterior	Leakage, Outgassing, Health
Drop	PlaneGard, 0 batteries, Water misted over exterior	Leakage, Outgassing, Health
	CellBlock, 0 batteries, Water misted over exterior	Leakage, Outgassing, Health

Batteries are not required to test the ability of the containers to control most hazards. The thermal test is focused on testing the internals of the container and will use a heater to simulate a battery on fire as the test will be better controlled and repeatable. If the containers hold up to 730 °C for 2 minutes, then the hazards such as fire/heat and thermal runaway should be contained. The altitude, vibration, and drop tests are focused on testing the structural integrity of the containers. If water is proven to be kept out of the containers, we can reasonably conclude that leakage and outgassing will be contained within the container in the case of a thermal event. If the containers pass all of these tests, then the hazard to human health should be demonstrated as controlled.

This is considered reasonable since the focus of the tests is the effectiveness of how the containment devices hold up to all the identified hazards.

To test the ability of the containers to withstand rupture of a battery with fragmenting, it is recommended that thermal tests be run with a 10-pack of 18650 type high-discharge batteries that are damaged and connected to each other with a 90-100% SOC at the beginning of the test to force the batteries into a thermal runaway condition. The application of external charging during the test may be advisable to better ensure rupture.

4.0 Tests

TEST 1: ALTITUDE TEST

4.1.1 Scope:

The purpose of this test is to evaluate the effect of high altitude, low temperature conditions on containers for damaged or defective lithium ion batteries.

4.1.2 Procedure:

The sample container will be tested at a pressure of 11.6 kPa for 6 hours. The temperature will be maintained at 72 ± 3 °C. This pressure simulates an altitude of 51,000 feet. For containers designed to be watertight, water indicating paper will be placed on the inside of the container prior to testing. One of each sample container will be subjected to testing one time.

After 6 hours, the sample will be removed and inspected for signs of damage. The container will also be sprayed with water from multiple angles. A “PASS” result is achieved if the sample container maintains its structural integrity and there are no holes, cracks, or other damage that would result in a loss of function of the packaging. For containers designed to be watertight, the water indicating paper must not be active for a “PASS” result.

For the detailed procedure see Training Module SMS-5610 in Appendix A.

TEST 2: THERMAL TEST

4.1.3 Scope:

The purpose of this test is to evaluate the effect of high temperature thermal hazards associated with thermal runaway of a lithium ion battery on sample containers.

4.1.4 Procedure:

A small, high temperature heater inside a steel block designed to simulate a lithium ion battery pack will be placed inside the sample container and heated. The heater will be heated to a maximum temperature of 730 °C for 2 minutes. Thermocouples will be used to monitor and record at least two separate areas inside the container and two areas on the external surface of the container. One of each sample container will be subjected to testing.

After 2 minutes, the heater will be turned off and the temperature will be monitored for 1 hour. The container will be allowed to cool, and the sample container inspected for signs of damage.

A “PASS” result is achieved if the sample container maintains its structural integrity, no holes or cracks are observed, and the external surface temperature of the container did not exceed 50 °C.

For the detailed procedure see Training Module SMS-5610 in Appendix A.

TEST 3: VIBRATION TEST

4.1.5 Scope:

The purpose of this test is to evaluate the effect of vibration during transport on sample containers.

4.1.6 Procedure:

The sample container will be secured to a vibrating table and subjected to vibrations for 6 hours. For containers designed to be watertight, water indicating paper will be placed on the inside of the container prior to testing. One of each sample container will be subjected to testing one time.

Samples will be inspected before and after testing to note any physical damage. The container will also be sprayed with water from multiple angles. A “PASS” result is achieved if the sample container maintains its structural integrity and there are no holes, cracks, or other damage that would result in loss of function of the packaging. For containers designed to be watertight, the water indicating paper must not be active for a “PASS” result.

For the detailed procedure see Training Module SMS-5610 in Appendix A.

TEST 4: DROP TEST

4.1.7 Scope:

The purpose of this test is to evaluate the effect of a free fall impact on sample containers.

4.1.8 Procedure:

The sample is lifted and dropped remotely. For containers designed to be watertight, water indicating paper will be placed on the inside of the container prior to testing. Two of each sample container will be subjected to testing one time.

Samples will be inspected before and after testing to note any physical damage. The container will also be sprayed with water from multiple angles. A “PASS” result is achieved if the sample container maintains its structural integrity and there are no holes, cracks, or other damage that would result in loss of function of the packaging. For containers designed to be watertight, the water indicating paper must not be active for a "PASS" result.

For the detailed procedure see Training Module SMS-5610 in Appendix A.

TEST 5: FUNCTIONAL TEST

4.1.9 Scope:

The purpose of this test is to evaluate the effectiveness of the containers to control the hazards after undergoing rough handling.

4.1.10 Procedure:

Batteries are placed in a thermal runaway condition within the container prior to the container undergoing Tests 1-4 to establish a baseline capability to control each of the identified hazards.

The same test is performed after the container has undergone Tests 1-4 to establish its effectiveness after rough handling and environmental conditions.

Appendix B – Training Modules

Title: **Altitude Test**	No.: **SMS-5610**	Page: **1 of 2**
Reference: **SMS-5610 TA-2 Lithium Ion Battery Containers**	Rev: **0**	Date:

1.0	**SCOPE**	
1.1	This document describes the basic safety requirements and procedures for conducting altitude testing on containers for damaged or defective lithium ion batteries. Sample preparation, test configuration, and test operations for the test are discussed. The procedure for analyzing, evaluating and interpreting the data is also described. Samples tested will include containers for damaged or defective lithium ion batteries. This test determines the effect of low-pressure conditions on containers for damaged or defective lithium ion batteries.	
1.2	**HSE Equipment/ Facilities**	**Function**
1.2.1	Ventilation system	Prevents the operator from being exposed to harmful gases that may be released when a material propagates by removing them from the testing area.
1.2.2	Operator shielding	Prevents the operator from being contaminated with unreacted combustible or flammable material and protects the operator from reactions that occur during testing.
2.0	**MATERIALS AND EQUIPMENT LIST**	
2.1	**Material**	**Quantity/ Description**
2.1.1	Test articles: Containers for damaged/ defective lithium ion batteries	Burn bag - fire-proof bag
		Lithium Fire Gard (formerly PlaneGard) - a metal container designed to mitigate the hazards of damaged lithium ion batteries
		Cylindrical battery containment kit - Consists of a drum/ pail with a lid and a bag of absorbent material
2.1.2	Solvent	Commercial grade acetone, methanol, or equivalent
2.1.3	Wiping tissues	Kimwipes or equivalent
2.1.4	Bags	Pink polyethylene antistatic or conductive Velostat
2.1.5	Non-conductive inspection tools	Made from or covered with non-conducting material
2.2	**Equipment**	**Quantity/ Description**
2.2.1	Altitude/ environmental chamber	Altitude/ environmental chamber NOTE: The test chamber must be able to simulate pressures as low as that found at 25,000 feet elevation.
2.2.2	Sample container	Appropriate container for storing and transporting damaged batteries
2.2.3	Camera	For still photographs
2.2.4	Camera tripod and housing	
2.2.5	Calibration software	

2.2.6	Temperature/ humidity probe	Data record
2.2.7	Tape	Teflon or equivalent, 25-50 mm (1-2 inches) wide, 0.15 mm (0.006 inches) thick
2.2.8	Marker	Black felt tip
2.2.9	Weather Meter	For recording laboratory conditions
3.0	**TEST SETUP PROCEDURE**	
3.1	**Operational Check and Verification**	
3.1.1	NOTE: An operational check is normally conducted daily.	
3.1.2	Inspect the test equipment for signs of wear, foreign objects, loose components, and other anomalies	
3.2	**Machine Set-up**	
3.2.1	NOTE: A camera is required for the test and the equipment should be set up in accordance with the corresponding procedure.	
3.2.2	Place sample container into the test chamber.	
3.2.3	For containers designed to be watertight, water indicating paper will be placed on the inside of the container prior to testing. One of each sample container will be subjected to testing one time.	
3.2.4	Set temperature settings to 72 ± 3 °C	
3.2.5	Set pressure/ altitude settings to a maximum of 11.6 kPa	
3.2.6	Turn on the power source to the chamber and close the door securely.	
3.3	**Running a Test**	
3.3.1	NOTE: Add or remove lighting to better detect smoke or spark/ flash respectively. **WARNING: Stand behind the safety shield during testing**	
3.3.2	Store the sample container at 11.6 kPa for 6 hours.	
3.3.3	After 6 hours, the sample will be removed and inspected for signs of damage. The container will also be sprayed with water from multiple angles.	
3.3.4	If the sample experiences leakage, venting, disassembly, rupture, or fire, immediately turn on the exhaust system until all gases emitted from the reaction are removed from the area.	
4.0	**POST-TEST PROCEDURE**	
4.1	Turn the machine off and unplug.	
4.2	Inspect the sample container.	
4.3	Determine whether the trial produced a “PASS” or “FAIL” result per section 5.0.	
5.0	**CRITERIA FOR ANALYZING RESULTS**	
5.1	A “PASS” result is achieved if the container meets the following requirements: i. There were no fragments observed leaving the container during the test ii. The container maintains structural integrity iii. No holes are observed in the container after the test iv. For containers designed to be watertight, the water indicating paper must not be active for a “PASS” result.	
5.2	Differentiation between a “PASS” or “FAIL” result can be completed by review of the video or human observation. Instrumentation that records the test outcome for review is preferred. Instrumentation is preferred over human observation to limit test subjectivity.	

SMS SAFETY MANAGEMENT SERVICES

Training Module

Title: **Thermal Test**	No.: **SMS-5610**	
Reference: **SMS-5610 TA-2 Lithium Ion Battery Containers**	Rev: **0**	Date:

1.0	**SCOPE**	
1.1	This document describes the basic safety requirements and procedures for conducting thermal testing on containers for damaged or defective lithium ion batteries. Sample preparation, test configuration, and test operations for the test are discussed. The procedure for analyzing, evaluating, and interpreting the data is also described. Samples tested will include containers for damaged or defective lithium ion batteries. This test assesses the effectiveness of the sample containers at mitigating thermal hazards associated with elevated temperatures generated by a lithium ion battery in a thermal runaway scenario.	
1.2	**HSE Equipment/ Facilities**	**Function**
1.2.1	Ventilation system	Prevents the operator from being exposed to harmful gases that may be released when a material propagates by removing them from the testing area.
1.2.2	Operator shielding	Prevents the operator from being contaminated with unreacted combustible or flammable material and protects the operator from reactions that occur during testing.
2.0	**MATERIALS AND EQUIPMENT LIST**	
2.1	**Material**	**Quantity/ Description**
2.1.1	Test articles: Containers for damaged/ defective lithium ion batteries	Burn bag - fire-proof bag
		Lithium Fire Gard (formerly PlaneGard) a metal container designed to mitigate the hazards of damaged lithium ion batteries
		Cylindrical battery containment kit Consists of a drum/ pail with a lid and a bag of absorbent material
2.1.2	Solvent	Commercial grade acetone, methanol, or equivalent.
2.1.3	Wiping tissues	Kimwipes or equivalent
2.1.4	Bags	Pink polyethylene antistatic or conductive Velostat
2.1.5	Non-conductive inspection tools	Made from or covered with non-conducting material
2.2	**Equipment**	**Quantity / Description**
2.2.1	Small heater	Microheater/ ceramic resistance heater

2.2.2	Thermocouples	For measuring external surface temperature of the sample containers
2.2.3	Sample container	Appropriate container for storing and transporting damaged batteries
2.2.4	Camera	For still photographs
2.2.5	Camera tripod and housing	
2.2.6	Calibration software	
2.2.7	Temperature/ humidity probe	Data record
2.2.8	Tape	Teflon or equivalent, 25-50 mm (1-2 inches) wide, 0.15 mm (0.006 inches) thick
2.2.9	Marker	Black felt tip
2.2.10	Weather meter	For recording laboratory conditions
3.0	**TEST SETUP PROCEDURE**	
3.1	**Operational Check and Verification**	
3.1.1	NOTE: An operational check is normally conducted daily	
3.1.2	Check sample container for damage	
3.1.3	Inspect the test chamber	
3.2	**Machine Set-up**	
3.2.1	Instrument the external surface of the sample container with thermocouples NOTE: Thermocouples should be centered on the external surface of the container	
3.2.2	Place the small heater inside the sample container	
3.3	**Running a Test**	
3.3.1	NOTE: Add or remove lighting to better detect smoke or spark/ flash respectively **WARNING: Stand behind the safety shield during testing**	
3.3.2	Heat the small heater inside the container to 730 °C for a time of 2 minutes	
3.3.3	Thermocouples will be used to monitor and record at least two separate areas inside the container and two areas on the external surface of the container	
3.3.4	After 2 minutes, the heater will be turned off and the temperature will be monitored for 1 hour. The container will be allowed to cool, and the sample container inspected for signs of damage. Observe sample container for signs of disassembly, rupture, or fire	
3.3.5	If the sample container experiences disassembly, rupture, or fire, immediately turn off the heater and turn on the exhaust system until all gases emitted from the reaction are removed from the area	
4.0	**POST-TEST PROCEDURE**	
4.1	Turn the machine off and unplug	
4.2	Determine whether the trial produced a “PASS” or “FAIL” result per section 5.0	

5.0	**CRITERIA FOR ANALYZING RESULTS**
5.1	A “PASS” result is achieved if the container meets the following requirements: i. There were no hazardous flames or fragments observed leaving the container during or after the test ii. The container maintains structural integrity iii. No holes are observed in the container after the test iv. External surface temperature of the container did not exceed 50 °C (measured by thermocouples)
5.2	Differentiation between a “PASS” or “FAIL” result can be completed by review of the video or human observation. Instrumentation that records the test outcome for review is preferred. Instrumentation is preferred over human observation to limit test subjectivity.

SAFETY MANAGEMENT SERVICES

Training Module

Title: **Vibration Test**	No.: **SMS-5610**	
Reference: **SMS-5610 TA-2 Lithium Ion Battery Containers**	Rev: **0**	Date:

1.0	**SCOPE**	
1.1	This document describes the basic safety requirements and procedures for conducting vibration testing on containers for damaged or defective lithium ion batteries. Sample preparation, test configuration, and test operations for the test is discussed. The procedure for analyzing, evaluating, and interpreting the data is also described. Samples tested will include containers for damaged or defective lithium ion batteries. This test simulates vibration during transport.	
1.2	**HSE Equipment/ Facilities**	**Function**
1.2.1	Ventilation system	Prevents the operator from being exposed to harmful gases that may be released when a material propagates by removing them from the testing area.
1.2.2	Operator shielding	Prevents the operator from being contaminated with unreacted combustible or flammable material and protects the operator from reactions that occur during testing.
2.0	**MATERIALS AND EQUIPMENT LIST**	
2.1	**Material**	**Quantity/ Description**
2.1.1	Test articles: Containers for damaged/ defective lithium ion batteries	Burn bag - fire-proof bag
		Lithium Fire Gard (formerly PlaneGard) a metal container designed to mitigate the hazards of damaged lithium ion batteries
		Cylindrical battery containment kit Consists of a drum/ pail with a lid and a bag of absorbent material
2.1.2	Water	To check for leaking of sample containers
2.1.3	Solvent	Commercial grade acetone, methanol, or equivalent.
2.1.4	Wiping tissues	Kimwipes or equivalent
2.1.5	Bags	Pink polyethylene antistatic or conductive Velostat
2.1.6	Non-conductive inspection tools	Made from or covered with non-conducting material
2.2	**Equipment**	**Quantity/ Description**
2.2.1	Vibration test machine	For conducting the vibration test
2.2.2	Sample container	Appropriate container for storing and transporting damaged batteries
2.2.3	Camera	For still photographs
2.2.4	Camera tripod and housing	
2.2.5	Calibration software	

2.2.6	Temperature/ humidity probe	Data record
2.2.7	Tape	Teflon or equivalent, 25-50 mm (1-2 inches) wide, 0.15 mm (0.006 inches) thick
2.2.8	Marker	Black felt tip
2.2.9	Weather meter	For recording laboratory conditions
3.0	**TEST SETUP PROCEDURE**	
3.1	**Operational Check and Verification**	
3.1.1	NOTE: An operational check is normally conducted daily	
3.1.2	Inspect test equipment for signs of wear, foreign objects, loose components, and other anomalies	
3.2	**Test Set-up**	
3.2.1	NOTE: A camera is required for the test and the equipment should be set up in accordance with the corresponding procedure	
3.2.2	For containers designed to be watertight, water indicating paper will be placed on the inside of the container prior to testing. One of each sample container will be subjected to testing one time.	
3.3	**Running a Test**	
3.3.1	NOTE: Add or remove lighting to better detect smoke or spark/ flash respectively **WARNING: Stand behind the safety shield during testing**	
3.3.2	Vibrate the test sample for 6 hours	
4.0	**POST-TEST PROCEDURE**	
4.1	Turn the machine off and unplug	
4.2	The container will be sprayed with water from multiple angles. Inspect the sample container for damage or leaking.	
4.3	Determine whether the trial produced a “PASS” or “FAIL” result per section 5.0.	
5.0	**CRITERIA FOR ANALYZING RESULTS**	
5.1	A “PASS” result is achieved if the container meets the following requirements: i. No liquid is leaking from the container ii. The container maintains structural integrity iii. No holes are observed in the container after the test iv. For containers designed to be watertight, the water indicating paper must not be active for a “PASS” result.	
5.2	Differentiation between a “PASS” or “FAIL” result can be completed by review of the video or human observation. Instrumentation that records the test outcome for review is preferred. Instrumentation is preferred over human observation to limit test subjectivity.	

Training Module

Title: **Drop Test**	No.: **SMS-5610**	
Reference: **SMS-5610 TA-2 Lithium Ion Battery Containers**	Rev: **0**	Date:

1.0	**SCOPE**	
1.1	This document describes the basic safety requirements and procedures for conducting drop testing on containers for damaged or defective lithium ion batteries. Sample preparation, test configuration, and test operations for the test are discussed. The procedure for analyzing, evaluating, and interpreting the data is also described. Samples tested will include containers for damaged or defective lithium ion batteries. This test is used to determine whether a test unit can withstand a free-fall impact without losing the integrity of the container.	
1.2	**HSE Equipment/ Facilities**	**Function**
1.2.1	Ventilation system	Prevents the operator from being exposed to harmful gases that may be released when a material propagates by removing them from the testing area.
1.2.2	Operator shielding	Prevents the operator from being contaminated with unreacted combustible or flammable material and protects the operator from reactions that occur during testing.
2.0	**MATERIALS AND EQUIPMENT LIST**	
2.1	**Material**	**Quantity/ Description**
2.1.1	Test articles: Containers for damaged/ defective lithium ion batteries	Burn bag - fire-proof bag
		Lithium Fire Gard (formerly PlaneGard) a metal container designed to mitigate the hazards of damaged lithium ion batteries
		Cylindrical battery containment kit Consists of a drum/ pail with a lid and a bag of absorbent material
2.1.2	Water	To check for leaking of sample containers
2.1.3	Solvent	Commercial grade acetone, methanol, or equivalent.
2.1.4	Wiping Tissues	Kimwipes or equivalent
2.1.5	Bags	Pink polyethylene antistatic or conductive Velostat
2.1.6	Non-conductive inspection tools	Made from or covered with non-conducting material
2.2	**Equipment**	**Quantity/ Description**
2.2.1	Drop tower and lift system	For safely and securely lifting of a sample, the sample must be HEIGHT m
2.2.2	Release initiator	For dropping containers
2.2.3	Sample container	Appropriate container for storing and transporting damaged batteries
2.2.4	Camera	For still photographs

2.2.5	Camera tripod and housing	
2.2.6	Calibration software	
2.2.7	Temperature/ humidity probe	Data record
2.2.8	Tape	Teflon or equivalent, 25-50 mm (1-2 inches) wide, 0.15 mm (0.006 inches) thick
2.2.9	Marker	Black felt tip
2.2.10	Weather meter	For recording laboratory conditions
3.0	**TEST SETUP PROCEDURE**	
3.1	**Operational Check and Verification**	
3.1.1	NOTE: An operational check is normally conducted daily	
3.1.2	Inspect test equipment for signs of wear, foreign objects, loose components, and other anomalies	
3.2	**Test Set-up**	
3.2.1	NOTE: A camera is required for the test and the equipment should be set up in accordance with the corresponding procedure	
3.2.2	Place sample in the container and close container	
3.2.3	For containers designed to be watertight, water indicating paper will be placed on the inside of the container prior to testing. Two of each sample container will be subjected to testing one time.	
3.2.4	Secure the sample container to drop machinery	
3.3	**Running a Test**	
3.3.1	NOTE: Add or remove lighting to better detect smoke or spark/ flash respectively **WARNING: Stand behind the safety shield during testing**	
3.3.2	Lift the test sample container to a specified height and then remotely drop it	
4.0	**POST-TEST PROCEDURE**	
4.1	The container will also be sprayed with water from multiple angles. Inspect the sample container for leaks and damage.	
4.2	Determine whether the trial produced a "PASS" or "FAIL" result per section 5.0.	
5.0	**CRITERIA FOR ANALYZING RESULTS**	
5.1	A "PASS" result is achieved if the container meets the following requirements: i. No liquid is leaking from the container ii. Container maintains structural integrity iii. No holes are observed in the container iv. For containers designed to be watertight, the water indicating paper must not be active for a "PASS" result	
5.2	Differentiation between a "PASS" or "FAIL" result can be completed by review of the video or human observation. Instrumentation that records the test outcome for review is preferred. Instrumentation is preferred over human observation to limit test subjectivity.	

Appendix C – Test Data

Following are the raw data from the thermal tests for each case that was tested. All data for the vibration, drop and altitude tests were included in the body of the report.

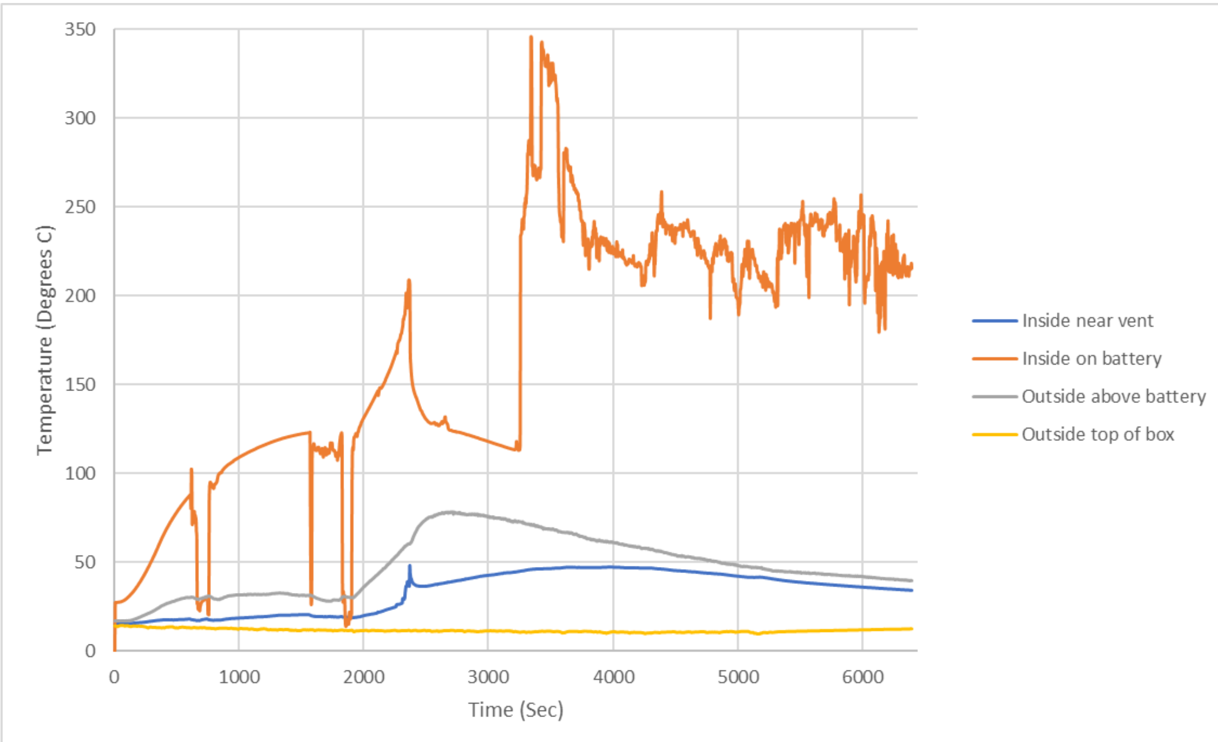

Figure C-1: Thermal Test Temperature Data for Lithium Fire Guard PG100

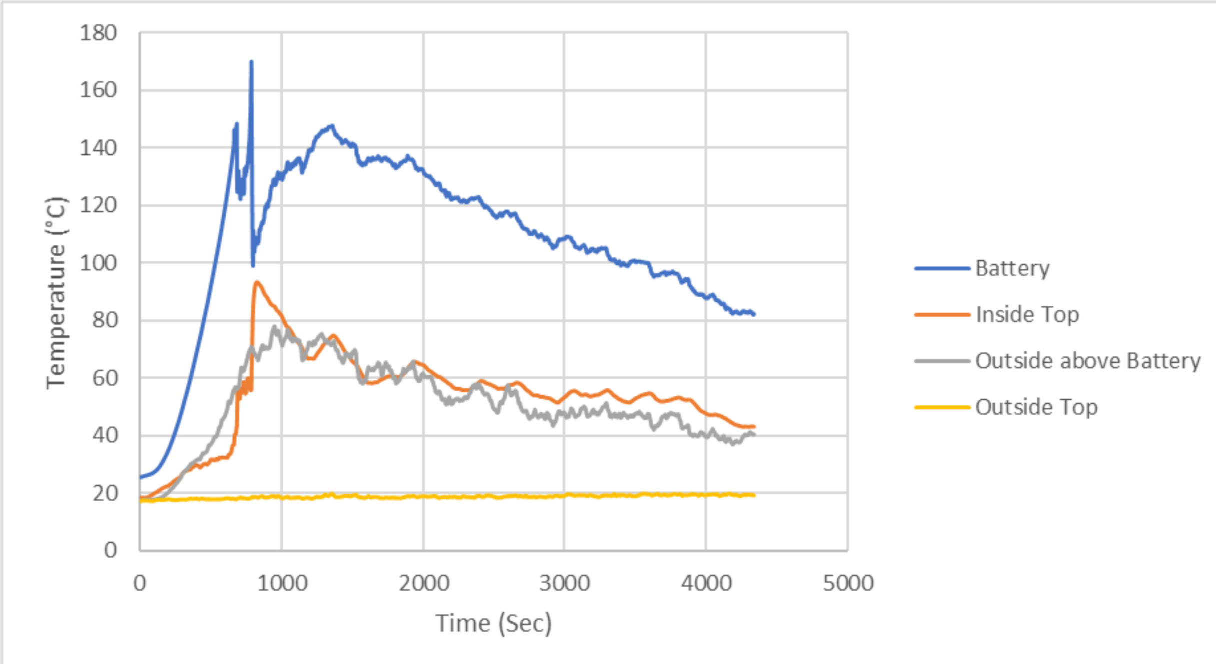

Figure C-2: Thermal Test Temperature Data for Brimstone Battery Fire Containment Bag

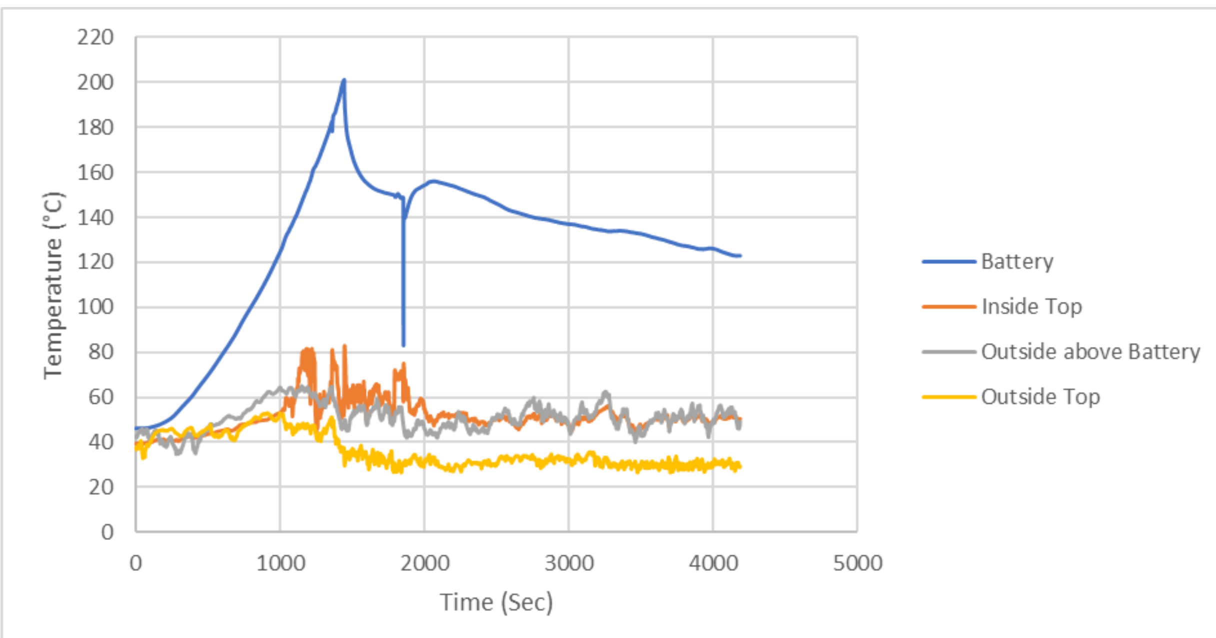

Figure C-3: Thermal Test Temperature Data for Fire Containment Concepts 14" PED SAFE-PAK

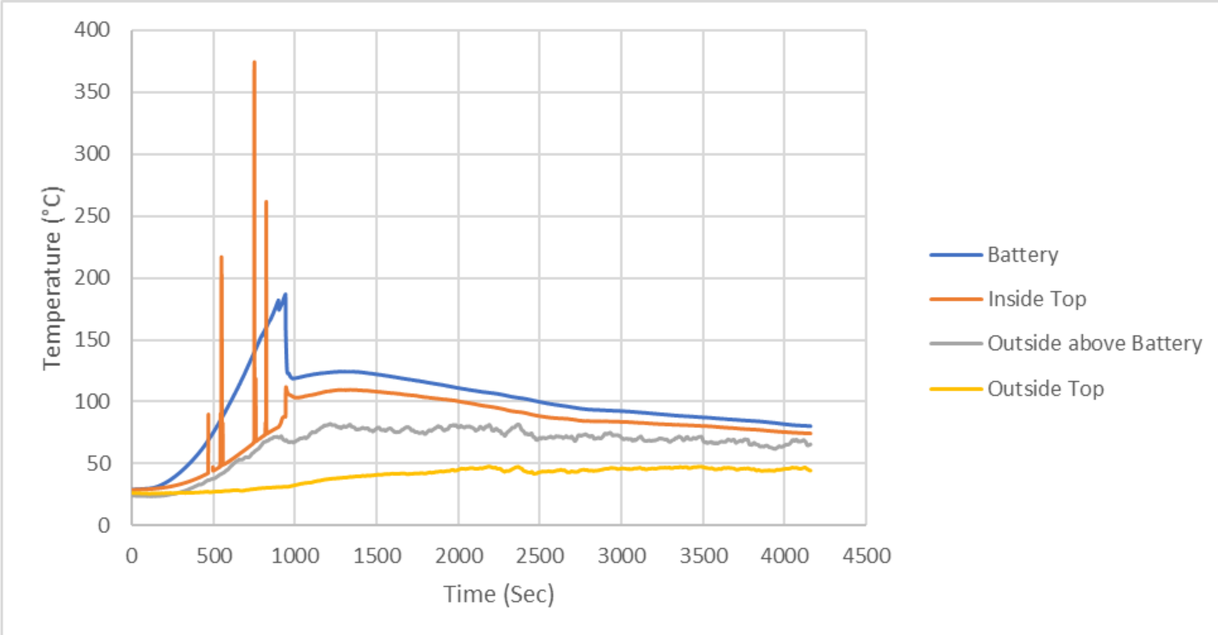

Figure C-4: Thermal Test Temperature Data for Newtex Z-Block™ Fire Containment Tote-Style Bag