SABATAIR
Deliverable 3a:
Test Plan for Additional Mitigating Measures

Task	**3**	Identification and assessment of additional mitigating measures to packaging and multi-layered approaches

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[1] Dissemination level: **PU** = Public, **PP** = Restricted to other programme participants (including the JU), **RE** = Restricted to a group specified by the consortium (including the JU), **CO** = Confidential, only for members of the consortium (including the JU)

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1. Structure of Report

Section 2 summarizes the topic of safety hazards of lithium batteries in air cargo transport. Initial data is presented in this section but is discussed more comprehensively in Section 4. This report observes that a 'safety gap' may have appeared between the growth in battery safety incidents and the growth of the lithium battery market. Such a 'safety gap' could indicate a need for a revised or new safety recommendations to be proposed to keep up with the development of lithium ion and lithium metal battery markets. Therefore, the reasons behind the apparent 'safety gap' needs to be carefully investigated.

Section 3 provides a brief statement of work review for Task 3.

Section 4 presents scenarios of lithium battery air cargo safety events with supporting statistics. The scenarios include: details from incidents involving crashes of air cargo planes; battery cargo fires; various hazard scenarios relating to batteries and their cargo packaging; descriptions of battery hazards; thermal runaway and related events of cell rupture and electrolyte leakage are given.

Section 5 summarizes the existing packaging solutions for lithium batteries.

Section 6 presents the core part of the report, namely, proposed mitigating measures to be used in addition to packaging. A Test Plan for Additional Mitigating Measures (**Appendix A**) is presented. The Test Plan is provided in an Excel table format and therefore is presented as an accompanying file despite it being an integral part of this report. The Test Plan table includes: a comprehensive survey of possible mitigation measures, their target levels, and identifies which measures would benefit from testing within the scope of the Sabatair project. This section covers the information that forms the basis for the Test Plan table, provides a review of possible hazardous events, their causes and mitigation measures proposed by Sabatair for consideration. The review covers the whole spectrum of scale from cargo compartments, packaging, mitigating measures in addition to packaging, and cell level items.

Section 7 describes an early warning smart diagnostic software mitigation solution developed by ALGOLiON as an innovative contribution of this project.

Appendix B provides an extensive summary of real cargo aviation events involving smoke, fire, extreme heat or explosion involving either lithium batteries or unknown battery types.

2. Introduction

The scope of the Sabatair project, as defined in the Tender (N° MOVE/C2/2016-353), is to propose and evaluate specific packaging solutions and evaluate other potential mitigating measures to be used with packaging for enhancing air cargo transport safety of lithium metal and lithium ion cells. In this instance, cells are defined as individual units, not electrically connected in multi-cell batteries. It should be noted that the scope does not include devices containing such cells or batteries.

Quoting directly from the Tender,

> *"Subsequent testing performed by the FAA proved that the current cargo compartment fire suppression systems are not capable of controlling fires with lithium metal- and lithium ion- batteries, and therefore, shipments of these batteries compromised the safety of the aircraft. The increase in accidents and incidents with lithium batteries and the fact that current measures seem to not be enough to prevent a potential catastrophe has driven ICAO to approve a ban for lithium metal and ion batteries to be transported as cargo in passenger aircraft until proper solutions are eventually developed and implemented. The provisions for transport of dangerous goods are contained in the ICAO Doc. 9284, the Technical Instructions for the Safe Transport of Dangerous Goods by Air (Technical Instructions). These are referred by the European Operational rules, Commission Regulation (EU) No 965/2012 (Air OPS).*
>
> *The so-called "class C" cargo compartments acc. to CS25.857(c) are required for non-accessible cargo compartments (typically underfloor) on passenger airplanes to be equipped with a build in fire suppression system, currently based on Halon 1301. Within the EU the usage of this agent is limited due to its ozone depletion potential. Halon is therefore earmarked for replacement with the industry engaged in developing suitable alternatives. However, so far, no fire suppression agent (including Halon) is effective in dealing with lithium fires."*

2.1. Lithium Batteries

In this report, the term lithium battery refers to both single cells and multiple cells that are electrically connected and includes both lithium metal and lithium ion chemistries.

Lithium rechargeable batteries are the battery system of choice for the over 2 billion consumer electronic devices produced each year, various types of electric vehicles, and in many aerospace, medical and defence applications. The lithium ion battery market, with sales of $21 billion globally in 2017, is growing at about 16% per year according to industry sources like Avicenne Energy Market Research Company. The majority of the 9 billion cells produced annually need to be transported, many by air, from point of manufacture to end-users and device makers around the world.

It is no surprise that air transportation of these batteries, particularly when not shipped in accordance with the regulations, may be dangerous and of mounting concern as the number of safety incidents appears at a faster rate than the progressive increase in battery sales volume. These accelerated rates of safety events are illustrated, for example, in data collected by the US Federal Aviation Administration (FAA) for aviation cargo and passenger baggage events involving smoke, fire, extreme heat or explosion from lithium or unknown battery types.

2.2. Safety Gap

As noted in the Tender for this project, there has been an increase in safety incidents with lithium batteries over the past years. This is evidenced in data sources available to EASA (including the European Central Repository).

Figure 1, compiled by the FAA, shows a steep rise in aviation cargo and passenger plane lithium battery safety events starting around 2012 and up to May 2, 2018.

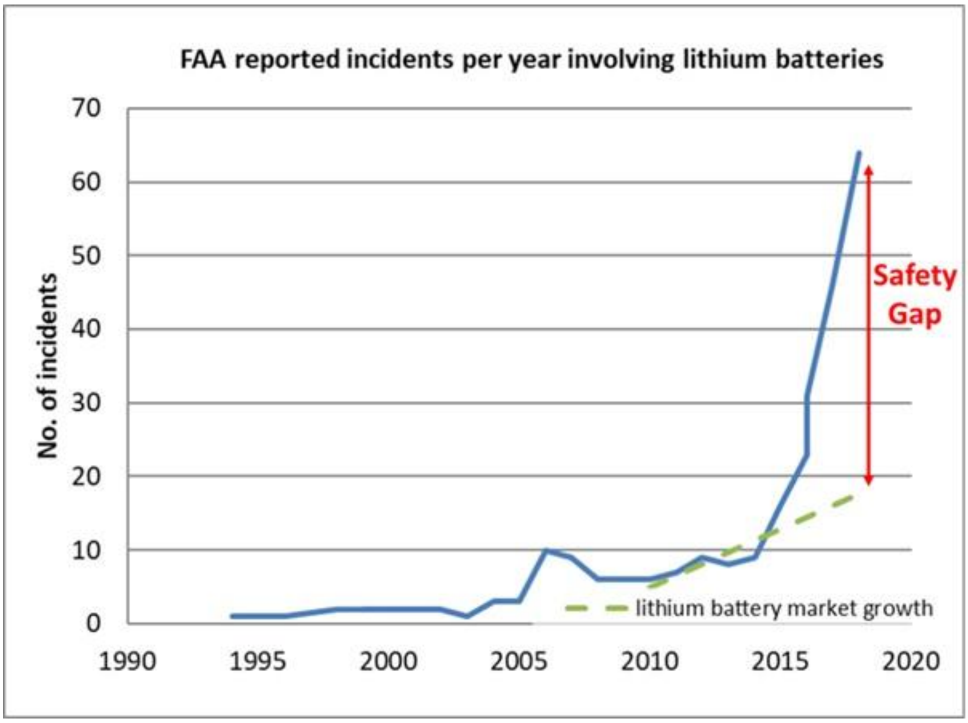

***Figure 1:** Aviation cargo and passenger baggage events involving smoke, fire, extreme heat or explosion involving lithium batteries or unknown battery types, FAA Office of Security and Hazardous Materials Safety, as of May 2, 2018. A* "safety gap" *has opened up where the hazards are growing faster than the market itself.*

The US FAA Office of Security and Hazardous Materials Safety has compiled a list of events for cargo (and passenger) airplane incidents involving lithium batteries carried as cargo or baggage (both in air and ground transportation). 206 such events have been recorded since March 20, 1991 (c.f. **Appendix B**) as of May 2, 2018 [1].

Table 1 Situations and frequencies of aviation cargo and passenger baggage events (grouped as non-passenger cabin events) involving smoke, fire, extreme heat or explosion caused by lithium batteries or unknown battery types, as from [1].
subcategorises the cargo events.

Situation	Number of incidents	As percent of total incidents
Discovered during the aircraft loading process	34	61%
Discovered during the aircraft un-loading process	15	27%
Damaged during the handling prior to loading onto craft	4	8%
Damaged by drop impact	1	2%
Associated with an aerosol can	1	2%

Table 1 *Situations and frequencies of aviation cargo and passenger baggage events (grouped as non-passenger cabin events) involving smoke, fire, extreme heat or explosion caused by lithium batteries or unknown battery types, as from [1].*

The rate of safety incidents reached an average of two per month (24 per year) by 2016. As if this alarming statistic is not worrisome enough, the most recent statistics [1] show that this already high level has more than doubled to 5 incidents a month (more than 1 per week) mainly occurring in the passenger cabin for unpackaged batteries or equipment for flights tracked just by the FAA. This jump far outstrips the 16% per annual growth rate of the lithium battery market. We refer to this as a "*safety gap*" which has opened where hazardous events are growing faster than the battery market itself (**Figure 1**). The full list of cargo events is provided in 0. Some of the examples shown in Appendix B are related to undeclared lithium batteries; those shipped not in accordance with the regulations; and many for lithium batteries contained in equipment where in some instances the device becomes active (powered on) creating a hazard during transport in packaging enclosures and not as result of a lithium battery fault per se.

New approaches for safe air transport of lithium batteries as cargo could be investigated. Task 3 contributes to the identification and assessment of additional mitigating measures to packaging for these batteries as cargo for air transport.

For this Task 3 we performed an analysis of the categories of the FAA listed events [1]. The statistics are presented in **Table 1.** The categories are related to the Fault Tree categorization of possible causes of fire events written in Task 1 documentation of the Sabatair project and summarized in Section 4.3 of this report.

The data shows that:

- 61% of the events occurred before the cells were loaded onto cargo aircraft.
- The number of events is high and increasing.
- 27% occurred after landing including during unloading of the aircraft and that potentially the event could have started during flight.
- Handling procedures of packages for loading onto aircraft contributed to several fires:
  - Packages were dropped (impact) that caused intra- or internal cell shorting leading to thermal runaway.
  - Packages were damaged by the conveyor system in the logistics centre.
  - Improper arrangement of cells lead to shorts. While this is not an air operator handling issue, but rather a shipper responsibility, it may have influences during the flight.

<u>Analysis and Conclusions:</u>

Since most incidents (88%) occurred before the flight took off or after landing during unloading (the initiation may have occurred during the flight), it seems that on one hand a slight shift in the timing of the fire event could have resulted in mid-flight fire accidents, diverted flights and perhaps even crashes. On the other hand, one can present a case that the fires occurred shortly after some sort of incident *before* take-off thus enabling measures to be taken.

The investigators did not have sufficient tools to determine the exact cause of the thermal runway fire or explosion – only ten events out of 54 could be attributed to specific causes:

- 3 were concluded to be due to a short circuit created by improper arrangement of the cells within the packaging. It was not indicated if the packaging was compliant or not with existing standards and regulations.
- 1 was attributed to the package receiving an impact from being dropped. This may be due to non-compliant packaging since if the packaging met regulations, it should pass the UN drop test or a compliant packaging fell from a height greater than the one specified in the standard.
- 5 were categorized as being damaged during handling in logistics centres.
- 1 was due to involvement of an aerosol can.
- The remainder were listed as unknown causes.

Further analysis of the incidents can be summarized as:

- Some of the incidents occurred in batteries assembled into equipment.
- Some shipments were mislabelled as 'non-hazardous' or 'non-regulated' goods.

In most cases, the cause of the fires remains unknown. It could be beneficial to identify the most common sources of accidents in order to assess which are the correct measures to apply to prevent them from occurring and to differentiate between incidents in complaint versus non-compliant packaging. Therefore, in order to provide investigators with appropriate tools to analyse suspicious cells, Task 3 includes sub-Task 3.3 - Evaluation of the use of diagnostic algorithms as additional mitigating measure. This topic is covered in Section 7 of this report. Early warning capability technology for detecting and analysing lithium cells could be used as part of a multi-layered approach to mitigate safety events. The information provided by such diagnosis can be used to prevent thermal runaway fires.

This safety gap indicates that the causes of the dangers are probably not only due to the higher energy, larger size and lower cost of cells, but that they are becoming increasingly likely to be affected by other reasons that need to be investigated.

In light of this, it could be that new approaches for safe air cargo transport of lithium batteries are needed to prevent hazards as the quantity of lithium batteries transported by air is continually growing. As stated in the Tender (N° MOVE/C2/2016-353, Research Study, "Safe transport of lithium batteries by aircrafts"), testing performed by the FAA proved that the current cargo compartment fire suppression systems are not capable of controlling fires due to lithium metal and lithium ion- batteries, and therefore, shipments of these batteries compromised the safety of the aircraft. Additional mitigating measures besides the packaging and more advanced diagnostic technology both for identifying potential hazards and for the analysis of suspicious and post-accident cells could be considered. Task 3 contributes to the identification and assessment of additional mitigating measures to packaging for these batteries as air transport cargo.

3. Task 3: Identification and assessment of additional mitigating measures to packaging and multi-layered approaches

3.1. Overview of Objectives of Task 3

The goal of Task 3 is to propose additional mitigating measures that can be used together with packaging for dealing with the safety hazards posed by the air cargo transport of lithium batteries - viz. heat, fire, explosion, release of gases, ejection of fragments, their causal and contributory factors and their consequences.

This task covers the identification of possible measures to consider within a multi layered approach to increase the level of safety for the air transport of lithium batteries as cargo. This task includes a categorisation and critical review of the available hazard mitigation measures, besides packaging. The work also assesses efficiency, readiness level and cost effectiveness.

3.2. Scope of Test Work Plan

The Test Plan is summarized in the accompanying Excel file,

Sub-Task 3.1: A description of the set of reference scenarios that will be developed and selected for purpose of evaluation of the efficiency of the different mitigation measures. The review covers real life scenarios, foreseen failure modes and experimental plans for fire testing.

Sub-Task 3.2: The identification of a set of mitigation measures with appropriate justification including the supporting thermal calculation results. This work covers market screening and evaluation of potential commercially available and not-yet commercially available solutions for a second layer mitigating approach to increase the protection capability of packaging in conjunction with testing in Task 2.

Sub-Task 3.3: Evaluation of the use of diagnostic algorithms as additional mitigating measures. This is described in more detail in Section 7. This work study will evaluate, via testing in Task 2, how early warning diagnostic software protocols may be used to follow (a) the development of thermal runaway within a given cell, and (b) the propagation of fire within packages of lithium ion batteries and to provide early warning of possible hazardous events. The information provided by the data, generated from testing the diagnostic algorithms in Task 2 and Task 3, is expected to lead to improved understanding for developing safety standards and regulations.

4. Scenarios of Lithium ion and Lithium metal cell safety events

This section reviews various scenarios of safety events that have occurred in real life in aircraft. The safety events are suspected to have been caused by thermal runaway, fire or explosion of lithium ion and lithium metal batteries.

4.1. Categories of Failures

In discussing scenarios of lithium ion and lithium metal battery safety events, categories of lithium battery failures could be categorized and grouped according to the level of damage they might cause. The categories include:

- **Cell swelling:** caused by an increase of the cell's internal pressure.

- **Leakage:** when cell's internal liquid or organic vapours of the electrolyte solvent escape out of the cell in a slow process.

- **Rupture:** is a sudden opening of a battery and the resulting expulsion of some or all of its contents.

- **Bursting:** occurs by the rapid release of excessive chemical energy from the battery which can be blown apart following thermal runaway. Pressure waves are created which may cause considerable structural damage to surrounding cells and packaging. In cases of batteries containing flammable gases or solvents, a rupture may lead to secondary explosions if the flammable fuel/air mixtures are ignited. This damage may propagate the hazard to other cells and to the packaging.

- **Thermal runaway fire**: when a cell is heated, either due to an internal short or from an external source, above a certain temperature (usually above 130–150°C), exothermic chemical reactions between the electrodes and electrolyte begin to occur, raising its internal temperature. If the heat generated is dissipated effectively, the cell temperature will not rise abnormally. However, if the heat generated at a rate that is greater than what can be dissipated, the cell's temperature will continue to rise and will accelerate the chemical reactions causing even more heat production, eventually resulting in thermal runaway and consequently causing a fire and explosion as shown in **Figure 2**.

Figure 2: *18650 size lithium ion cell on fire after experiencing sudden thermal runaway.* [Source: *Dupré Minerals Limited, England]*

Thermal runaway is generally defined as a self-heating rate of the cell of 10°C/min or greater. At this self-heating rate, it is highly unlikely that any intervention could extinguish the consequent thermal runaway. Consequently, it is obligatory to identify the causes of these risks in order to prevent them early enough to avoid safety threats.

4.2. Real Scenarios that Resulted in Cargo Plane Crashes or Diverted Flights

According to IATA [2] (see **Table 2**) three major aircraft accidents, where lithium battery shipments were known to be on board as cargo are:

- Asiana Airlines, Jeju, South Korea on July 28, 2011.
- UPS, Dubai, UAE on September 3, 2010. It is not known if the lithium batteries carried as cargo initiated the fire. There were no declared fully regulated dangerous goods on board the aircraft.
- UPS, Philadelphia, USA on February 7, 2006. It is not known if the lithium batteries carried as cargo initiated the fire. There were no declared fully regulated dangerous goods on board the aircraft.

Of these accidents, lithium battery cargo was known or suspected to be involved in a significant way only in case number 1. These three incidents cover the two main scenarios of lithium ion or lithium metal battery fires on cargo planes, namely:

- The fire originated from the lithium battery cargo.
- The fire started elsewhere and then spread to the lithium battery cargo.

In two incidents, the fires broke out early into the flight. The third occurred during the descent.

Table 2: Three cargo **plane accidents** where lithium batteries are known, or suspected, to have been involved in a significant way. [Source: IATA, Three Accidents Involving Lithium Batteries, 1st Edition, 2016, [2]]

indicates that once a fire originates in a plane with large quantities of lithium batteries as cargo, the time it takes from ignition to uncontained fire is quite short: 17 minutes, 23 minutes and 27 minutes for accidents 1, 2 and 3 respectively.

	Accident/Incident #1 B744 Jeju	Accident/Incident #2 B744 Dubai	Accident/Incident #3 DC-8 Philadelphia
LI batteries on board	Yes	Yes	Yes
Declared?	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	27:45 minutes

Table 2: Three cargo plane accidents where lithium batteries are known, or suspected, to have been involved in a significant way. [Source: IATA, Three Accidents Involving Lithium Batteries, 1st Edition, 2016, [2]]

4.2.1. Incident Number 1 Synopsis

HL7604 Asiana Airlines crashed on 28 July 2011. The cause of this fatal accident was due to a fire developing on or near the pallets containing dangerous goods (i.e. flammable liquids, corrosive liquids, and lithium ion batteries (Class 3, 8 and 9)). No physical evidence of the cause of the fire was found. The fire rapidly escalated into a large uncontained fire, and this caused some portions of the fuselage to separate from the aircraft in mid-air, thereby resulting in the crash. A contributing factor was the difficulty to contain a large-scale fire only by the fire suppression process of a Class E cargo compartment that was not equipped with an active fire suppression system.

The investigation determined that cargo stored on the aircraft between Fuselage Station FS1 700 and the aft bulkhead had caught fire. A total of 2,092 kg was declared as dangerous goods, loaded near the left cargo door on the main deck. These goods consisted of flammable liquids, corrosive liquids and lithium ion batteries. All dangerous cargo had been placed onto two aircraft pallets and had been loaded without problems; no observation of damage or leakages was recorded. The goods had been previously stored according to regulations. It was impossible to say what caused the fire. The cargo was stored on the aircraft between FS 1700 and the aft bulkhead, which included (but is not limited to) the dangerous goods as described above.

Note: The consignment containing the lithium ion battery for a hybrid vehicle had flown on a previous flight from Osaka, Japan prior to carriage onboard AAR991. (See aircraft accident report ARAIB/AAR1105 ***1.18.3 Dangerous Goods).***

4.2.2. Incident Number 2 Synopsis

N571UP United Parcel Service (UPS) crashed on 3 September 2010 in Dubai. A large fire which developed in the palletised cargo area on the main deck at or near pallet positions 4 or 5, in Fire Zone 3 caused this fatal accident. It consisted of consignments of mixed cargo including a significant number of lithium type batteries (including button cells and lithium batteries contained in equipment) and other combustible materials. There were no declared fully regulated dangerous goods on board the aircraft. The fire escalated rapidly into a catastrophic uncontained fire.

The investigating authority report found "*with reasonable certainty*" that the fire, which caused the crash, originated in a cargo container which held thousands of lithium batteries, including small button cells and lithium batteries contained in equipment. The report made 36 recommendations for safety improvements, including improvements to systems that warn pilots of cargo hold fires, and use of additional systems to improve pilot visibility during aircraft fire scenarios. Partly as a result of this investigation, the International Civil Aviation Organization (ICAO) adopted a ban on the shipment of lithium metal batteries shipped alone as cargo aboard passenger aircraft. The prohibition came into effect on January 1, 2015.

4.2.3. Incident Number 3 Synopsis

The National Transportation Safety Board determined that the probable cause of the N748UP United Parcel Service accident on February 8, 2006 (**Figure 3**) was an in-flight cargo fire that initiated from an unknown source, which was most likely located within cargo container 12, 13, or 14 (which included lithium batteries contained in equipment). Contributing to the loss of the aircraft, as per the opinion of the NTSB, was that there were inadequate regulatory certification test requirements for smoke and fire detection systems and the lack of an on-board fire suppression system. The aircraft met all the required regulatory certification standards.

The first indication of the fire was the first officer's query to the other crew members about the smell of burning wood, which occurred about 20 minutes before the main cargo compartment Cargo Smoke warning light activated. The flight engineer first saw smoke when he exited the cockpit to close the main cargo air shut-off valve and black smoke emanated from the valve's access panel. About 2 minutes later, almost immediately after touchdown, the flight engineer reported that smoke had begun entering the cockpit. The smoke continued to worsen after the airplane came to a full stop, and the smoke in the cockpit became so thick that the two pilots could not see each other before they evacuated the airplane.

Figure 3: *On February 7, 2006, a Douglas DC-8 cargo plane suffered an in-flight cargo fire and made an emergency landing at Philadelphia International Airport. There were no injuries other than smoke inhalation affecting the crew, but the plane burned on the ground for several hours. [*Source: *AINOnline].*

4.2.4. Diverted Flights

According to an FAA AAL (American Airlines) special agent statement, one example of an in-flight interruption occurred on October 10, 1998 in which a fire warning diverted a cargo aircraft. The captain and the flight engineer inspected the cargo area. Both identified heat rising between pallets on a jet flat from a consignment containing 336 laptop computers. They also noticed a strange odour and suffered from lung irritation. After landing, fire fighters sprayed the pallet with fire retardant.

4.3. Fault Tree Analysis Scenarios

The Sabatair consortium has created a fault tree to predict the lithium batteries failure modes that are more likely related to the packaging. The failure modes, considered in the Fault Tree analysis, relate to the real events reviewed in 2.2. Safety Gap.

- Mechanical events that need to be considered in a comprehensive fault analysis which may lead to an internal short via a burst
- In separator or contact between the anode/cathode
- Penetration on packaging during flight
- Penetration on packaging before flight
- Impact on packaging during flight
- Impact on packaging before flight
- Vibration and shocks during transport to plane
- Vibration and shocks during flight
- Poor cell design
- Cell design weakness at low air pressure
- Cell design weakness at the flight low temperature

- Cell production weakness
- Burst separator (e.g., dendrite growth, low temperature during flight freezes electrolyte)
- Environmentally inappropriate conditions
- Fire outside container or pallets
- Ambient temperature too high
- Water or fluids from other cargo
- General events (that could also be a consequence of a safety event or thermal runaway)
- Flammable/toxic gas emission
- Flammable gas (or liquid electrolyte) leaking out of a packaging (slow process)
- Flammable gas release out of a packaging (fast process)
- Toxic gas (e.g. HF) leaking/ release out of a packaging
- Flammable gas (or liquid electrolyte) leaking/release into a packaging
- Heat or fire exposure
- Internal short circuit in a cell
- Combustion of a cell
- Thermal runaway in a cell
- External cell short circuit
- Fire propagation between cells
- Fire propagation between packagings
- Fire escaping package / ignition of released flammable gas
- Fire escaping ULD / ignition of released flammable gas
- Fire in lower deck
- Fire in main deck

4.4. Major Failure Risks as per ICAO/IATA

Lithium batteries are defined as dangerous goods by the United Nations. Specific requirements to make sure that they can be transported by air are determined by the International Civil Aviation Organization (ICAO) and these are then reflected in IATA's Dangerous Goods regulations. The IATA Dangerous Goods Board has estimated that on some flight routes, lithium batteries could be present in about 25% of the cargo shipments [5].

One of the major risks associated with the air transport of batteries is an external short-circuit of the battery. This may occur if battery terminals come into contact with the other packed batteries, metal objects or other conductive surfaces. Packaged cells must be separated in a manner to prevent external shorts and damage to the terminals.

4.5. Minimum Performance Standards for Fire Scenarios for Aircraft Cargo Compartments

This topic references the document "Minimum Performance Standards for Aircraft Cargo Compartment Halon Replacement Fire Suppression Systems" [3].

4.5.1. Fire Test Scenarios in Aircraft Cargo Compartments

Classification of cargo compartments are according to certification standards (*e.g.* FAA Part 25 of EASA CS-25). Almost all of today's cargo compartments belong either to the Class C cargo compartment (lower deck of passenger and cargo aeroplanes) as shown in **Figure 4:** Class C (left) and Class E (right) compartments illustration. [Source: The Boeing Company]., Class E cargo compartment (main deck of cargo aeroplanes) as shown in **Figure 4**and **Figure 5**. The cargo compartment classifications C and D existed in parallel after the second world war, but Class D was mostly deleted in favour of Class C, meaning that all former class D cargo compartments had to be retrofitted with a fire detection and a fire suppression system. Class C and D compartments are not accessible during flight.

The sidewall and ceiling liners of Class C cargo compartment must meet the requirements of CS-25 App. F Part III, which include showing the no flame penetration will occur within five minutes of direct exposure to a flame at a temperature equal to 927^{o}C ± 38ºC. Class C cargo compartments must include a means to shut off ventilation, a fire detection system and a built-in fire extinguishing or suppression system controllable from the flight deck. The objective is to ensure that the extinguishing agent will remain in its effective concentration while preventing at the same time the penetration of smoke to other cargo compartments and to occupied areas. Class E cargo compartments meet the same fire detection and ventilation control requirements as Class C but are not required to be equipped with liners meeting CS-25 App. F Part III standards and with a built-in fire suppression system. For Class E cargo compartments, the method of fire suppression is based on pressure equalization with the ambient atmosphere at a certain flight altitude, with consequent reduction of the partial pressure of oxygen in the compartment.

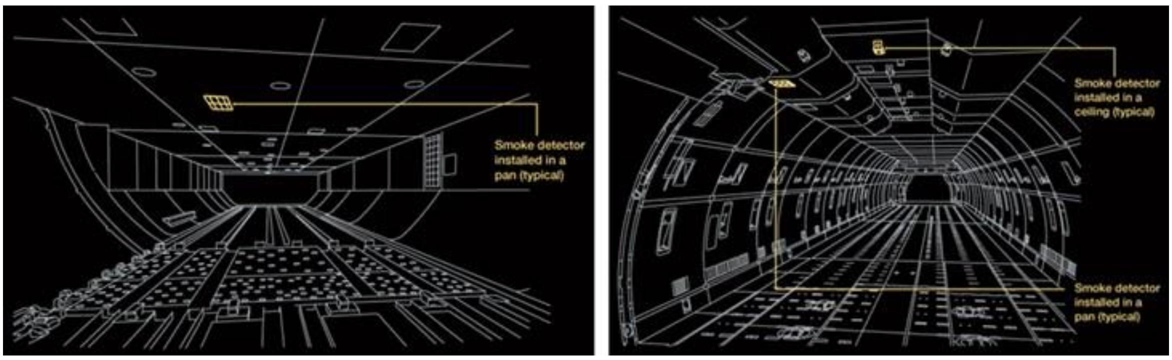

Figure 4: *Class C (left) and Class E (right) compartments illustration.* [Source: *The Boeing Company].*

***Figure 5**: Class E compartment. [*Source: *The Boeing Company].*

In the course of replacement of the ozone-depleting fire suppression agent Trifluorobromomethane (Halon 1301), which is used for cargo compartments since the introduction of McDonnell Douglas DC-10 some fifty years ago, an international group of aviation specialists steered by the US FAA established minimum performance standards (MPS) [3] any potential halon replacement has to fulfil. These minimum performance standards actually contain four fire scenarios which have to be passed to fulfil the MPS. Passing the MPS, i.e. showing at least the same suppression capabilities as todays Halon 1301, is a necessary means for any future cargo compartment fire suppression system on its way to become certified.

The four scenarios to be passed are:

- bulk-load fire (the cargo compartment is filled with standardized cardboard boxes filled with shredded paper)
- containerized-load fire (the cargo compartment is loaded with three LD-3 containers. One of the contains cardboard boxes filled with shredded paper)
- flammable liquid fire (surface burning) (a mixture of Jet A fuel and gasoline is placed in a pan located inside the cargo compartment)
- aerosol can explosion simulation (the explosion of a hairspray can is simulation by a dedicated apparatus)

All MPS fire tests are conducted in a mock-up simulating a wide-body aircraft's (DC-10) lower deck cargo compartment. The volume of the compartment is 56.6 ±2.8 m^3. The leakage rate from the compartment is 1.4 ±0.14 cubic metre per minute. The leakage from the compartment is configured to simulate the U shape of the cargo door seals that are on an actual aircraft. This may be done by installing perforated ducts inside the compartment in the shape of the perimeter of a cargo door and then venting those ducts outside the test article. A variable speed fan installed in the exit of the duct draws air out of the compartment. One-inch-diameter holes spaced at 12.7 cm intervals in a round, 10.2 cm diameter steel duct has been shown to be effective. The perforated ducts are installed on the side of the cargo compartment opposite the ignition packaging for the bulk and containerized-load fire scenarios. The return air that goes back into the compartment should be evenly distributed and not from any one location.

The simulated bulk and containerised-load fires, which are deep-seated fire scenarios, use shredded paper loosely packed in cardboard packaging to simulate the combustible fire load. The difference between these two tests is that in the bulk-load fire scenario the packagings are loaded directly into the cargo compartment, while in the containerised-load fire scenario, the packagings are stacked inside an LD-3 container. The flammable liquid surface burning test (Class B fire) uses 0.5 U.S. gallon (1.89 litres) of Jet A as fuel. The aerosol explosion simulation tests are executed by using an aerosol can simulator containing a flammable and explosive mixture of propane, alcohol, and water. This mixture ignites or explodes when it is exposed to an arc from sparking electrodes. At least five tests per MPS scenario must be conducted. These tests should be performed in a 2000-ft^3 simulated aircraft cargo compartment.

4.5.2. Bulk-Load Fire Scenario

The MPS bulk load fire scenario is the one scenario which is most appropriate for testing the cargo compartment fire suppression capabilities, active or passive, with respect to Lithium battery fires evolving from batteries stored in packages. It is thus explained in detail: the fire load for this scenario should consist of single wall corrugated cardboard packaging, with nominal dimensions of 45.7 cm by 45.7 cm by 45.7 cm. The weight per unit area of the cardboard is 0.5417 kg/m^2. The packaging should be filled with 1.1 kg of loosely packed standard weight office paper shredded into strips (not confetti) weighing 2.0 ±0.2 kg). The packaging should be conditioned to room standard conditions. The flaps of the packaging should be tucked under each other without using staples or tape. The packages should be stacked in two layers in the cargo compartment in a quantity representing 30% of the cargo compartment empty volume. For a 56.6-m^3 compartment, this requires 178 boxes. The packages should touch each other to prevent any significant air gaps between any of the packages. The fire inside the ignition package should be started by applying 115 VAC to a 2.1 m length of nichrome wire. The wire is wrapped around four folded (in half) paper towels. The resistance of the nichrome igniter coil should be approximately 7 ohms. The ignitor should be placed into the centre of a package on the bottom outside row of the stacked packages. Several ventilation holes should be placed in the side of the packaging to ensure that the fire does not self-extinguish. Ten 2.5 cm diameter holes have been shown to be effective.

In order to pass the test, the acceptance criteria are as follows: the average of the five test peak temperatures shall not exceed 377°C, starting 2 minutes after the suppression system is initially activated until the end of the test. In addition, the average of the five test peak areas under the time-temperature curve shall not exceed 4,974°C-min. The area should be computed from 2 minutes (t3) after the time of initial suppression system activation (t2) to 28 minutes after t3.

4.5.3. Plausible Scenarios for Ignition of Cells

In the case of thermal runaway due to an internal short circuit in one cell (which can be part of a small cluster), the cell will ignite and reach within a few dozen seconds to ca. 1000^{o}C. Within the next few minutes the hot ignition cell could propagate the fire to surrounding cells either by heating and starting a thermal runaway domino effect or by heating and igniting other flammable cargo.

In both cases the lithium ignition cell event will eventually fade away within a few dozen seconds (or few minutes in case of thermal runaway domino effect). If surrounding flammable cargo was ignited, then the C Class compartment fire suppression system needs to deal with the fire of flammable cargo. However, taking into account the time scale of the fire detection (up to one minute) followed by two more minutes within which the Halon 1301 concentration is required to reach its maximum concentration versus the time scale for the development of thermal runaway in surrounding cells, the system will need to be evaluated for whether the times scales of fire suppression and the kinetics of the thermal runaway propagated heating of secondary cells are matched. Note that the proposed SAE G-27 standard is intended to contain an event / thermal runaway inside the package.

For the kinetics of development of large lithium battery fires, NFPA tests can be consulted. They demonstrate that the fire does not develop faster than a fire of cardboard packaging. Therefore, the aircraft industry standards should be applicable. The results of the tests are available at:
https://www.nfpa.org/News-and-Research/Fire-statistics-and-reports/Research-reports/Hazardous-materials/Lithium-ion-batteries-hazard-and-use-assessment .

5. Review of Existing Packaging Solutions for Lithium Batteries

To review the packaging requirements for lithium batteries it is worthwhile to begin the discussion by classifying the batteries. Flow charts of UN requirements for lithium ion and lithium metal batteries are provided in the Sabatair Deliverable D2a.

Marking and labelling requirements for packages containing lithium batteries are referenced in [6]. The lithium battery handling label was replaced by a lithium battery mark effective 1 Jan 2019.

Currently packaging can consist of both soft and rigid walled materials. While they currently conform to relevant regulations, the flexible walled packaging is prone to penetration dangers.

5.1. 4G or 4GV UN Approved Containers

4G or 4GV containers using fibreboard and anti-static inners, such as vermiculite are marketed by several companies. The reader is referred to D2a for further information.

5.2. Plastic Rigid Boxes

Plastic boxes using flame retardant ABS materials (for example from Husqvarna, UK) or similar materials are discussed in the D2a deliverable report.

5.3. Metallic Containers

Metal containers are marketed by CCR for example. The reader is referred to the D2a deliverable report for more information.

Other metallic packaging types, by way of reference, have been used as the mitigating measure approved by the FAA on Boeing 787 Dreamliner aircraft (see **Figure 6**) for encasing the two operational lithium ion APU batteries which are connected to a vent through the fuselage to vent smoke. Each box weights 36 kg, adding 72 kg of weight to the plane. This translates to an additional fuel cost for the airlines. These are referenced as part of the aircraft equipment only and not related to cargo transport of lithium batteries.

Figure 6: *An example of a metal box required by the FAA to isolate the Boeing 787 Dreamliner operational batteries on-board the aircraft (there are two such units). [Source: The Boeing Company].*

5.4. Fire Containment Covers

Open aircraft pallets (ULDs) can be covered with fire containment covers (FCCs). These covers can isolate fire of temperatures up to 815°C for four hours. Like the fire-resistant containers, these covers provide protection from an adjacent fire as well as from one within [9]. Fire containment covers for structural ULDs have also recently come on to the market. These are operator fire mitigation measures not at the package level.

5.5. Soft-walled Supplementary Packaging (Over-packing)

Fabric containers, such as the one shown in **Figure 7**, are another possible solution for battery transportation. While not marketed specifically for the transportation of lithium batteries, the packaging is designed to withstand internal or external fires. There is however, no feature to prevent escape of gases. Such packaging could be used now by a single shipper as an "overpack" for a shipment or for individual cells within a packaging.

Figure 7: *An example of a protective bag with sample cells which could be used within a permitted rigid packaging.* [Source: *RCMart.com].*

Several materials have been suggested for both soft and rigid walled supplementary packaging. These include containers using fire-resistant material.

Thermal runaway temperatures can reach 800 – 1,000°C. One category of soft walled supplementary packaging is based on para-aramid. Para-aramid (Kevlar® and Twaron® [10] brand designations) decompose around 427-482°C (Kevlar) and about 500°C (Twaron®). These temperatures are well below the approximately 1,000°C reachable by thermal runaway events. Interestingly, in both cases, temperatures are not recommended to exceed 250°C. Therefore, there is a major issue with the containment material of this type if it is used in air transport battery packaging. This is because it will be unable to contain a fire for a prolonged period due to the material decomposing at temperatures lower than those reached in thermal runaway. Another issue is whether the packaging seal can contain the smoke, flames and projectiles generated from either a fire, leaked vapours or electrolyte fluid.

6. Additional Mitigating Measures to be used with Packaging and Test Plan Table (as Appendix A)

A comprehensive Test Plan for Additional Mitigating Measures has been prepared as part of this report. It lists possible mitigation measures identified by Sabatair and provides information on, among other items, their target level and which packagings would benefit from testing within or outside of the scope of the Sabatair project. Due to the large size of the table, it is provided as a separate Excel file. A description of this table is given in Appendix A. Each measure in the Table is described below. For the ease of the reader, the reference number for each mitigation method in the table is listed with each measure described in this Section.

This section presents a comprehensive survey of possible mitigation measures identified in the study by Sabatair. It should be noted that this is not exhaustive and that other mitigation measures may exist but have not been considered as part of this study.

It is realised that not all mitigation measures are relevant for all airlines, operators and shippers. As this document may be used by EASA in the future, outside of the Sabatair Project, the scope of the reviewed measures includes new innovations alongside existing ones in order to present a broad survey of this field. The latter are included for the additional reason that knowledge of them is important as they may need to be updated as progressive improvements are made in relation to batteries. Some of the measures were selected to be within the scope of the Sabatair project and others outside the scope; this classification is indicated in the table. Those within the scope of this project were ranked according to their priority for testing and in which task their evaluation will be performed. The overall prioritisation of the measures are provided in the table.

6.1 Cell/Battery Level

(Test Plan Table – No. 1 to 6)

6.1.1. Documentation about the Cell or Battery

(Test Plan Table – No. 1)

ICAO/IATA does not require a safety data sheet (SDS), or the UN 38.3 test data report as part of the documentation requirements when offering lithium batteries for transport [5, 6, 7]. Manufacturers and subsequent distributors of cells or batteries manufactured after 30 June 2003 must make available the test summary as specified in the UN Manual of Tests and Criteria, Part III, sub-section 38.3, paragraph 38.3.5. This test summary must be made available from 1 January 2020. See [6] for further details. Work is in progress by the UN on categorising batteries based on failure mode.

6.1.2. Shipment of Cells or Batteries for Recycling, Second Life Use or Prototypes

(Test Plan Table – No. 2)

Some of the batteries that are transported by air cargo, are destined for recycling, second-life or re-use usually for energy storage systems (ESS). Because such batteries may be in a degraded state relative to fresh batteries, they may present a greater potential hazard compared to fresh ones.

Due to their unknown origin and state of charge, batteries from recycle bins, it might be considered to treat them as charged batteries with a SOC of greater than 30%. This would put them outside the permitted range of maximum 30% SOC for air cargo transport.

According to ICAO/IATA [5, 6, 7], lithium batteries, identified by the manufacturer as being defective for safety reasons, or that have been damaged, that have the potential of producing a dangerous evolution of heat, fire or short circuit are forbidden for transport by air. (E. g. those being returned to the manufacturer for safety reasons). This applies also to lithium cells or batteries installed inside equipment such as mobile phones, laptops or tablets where the devices are subject to recall due to the safety concerns of the lithium cell or battery installed in the device.

According to ICAO/IATA [5, 6, 7], preproduction prototypes of lithium batteries or cells or low-production runs that have not been tested to the requirements of the UN manual of tests and criteria may be transported aboard cargo aircraft, if approved by the appropriate authority of the country of origin. In this case they can only be transported if the requirements in packing instruction 910 of the supplement to the ICAO Technical Instructions are met.

According to ICAO/IATA [5, 6, 7], shippers do not need to include any additional document or statement to certify that lithium ion batteries are at no more than 30% SoC. For lithium ion batteries shipped in accordance with Section IA or Section IB of Packing Instruction (PI) 965, which must be on a Shipper's Declaration, the Shipper's Declaration must include a certification statement: *"I declare that all of the applicable air transport requirements have been met."* By signing this, the shipper is signing a legal declaration to that all the applicable provisions of the DGR have been complied with. Including that the lithium ion batteries are at no more than 30% SoC. For Section II of Packing Instruction 965, the provision of the compliance statement "*lithium ion batteries in compliance with Section II of PI 965"* on the air waybill, will be taken by regulatory authorities as a legal declaration of compliance.

As a mitigation measure, it is suggested that early warning diagnostic software can be used for evaluating the state of safety of batteries before packing by the shipper. This can be considered as a means to identify faulty cells. Section 7 of this report discusses the capabilities of the early warning diagnostic algorithm of ALGOLiON. A diagnostic procedure could be developed for consideration for incorporation into a new regulation or standard as an additional mitigating measure.

6.1.3. Prohibition on transporting high safety risk cells

(Test Plan of Additional Mitigation Measures– No. 2)

Existing regulatory text covers prohibition of transporting high risk cells. Given that new lithium metal and lithium ion battery chemistries are being developed and commercialised, the categorisation of how these represent high safety risks may need to be reviewed.

6.1.4. Cell Design Features

(Test Plan of Additional Mitigation Measures– No. 3)

This section provides a short review of existing technology in cell design for mitigating hazard conditions. The following functionalities are used in the design of lithium cells and batteries:

- Abnormal temperature rise above a critical value is prevented. Many types of cells are designed with a positive temperature co-efficient (PTC) resettable current limiter.
- Temperature increases in the cell or battery shall be controlled by the design e.g. by limiting the current flow. One way this is achieved is by the use of shut-down separators. The flow of current through such separators is shut off when, above a certain critical temperature, the separator melts and so no longer is able to conduct ionic current within the cell. Another way is by use of an electrical current interrupt device (CID).
- Lithium cells and batteries shall be designed to relieve excessive internal pressure. This is intended to avoid a violent rupture. Many cells include a vent for this purpose.
- Lithium cells and batteries shall be designed to prevent an internal short-circuit under conditions of intended use. Some battery manufacturers use ceramic coated separators to inhibit the growth of internal shorts caused by dendrite growth of either lithium or copper.
- Lithium batteries containing cells or strings of cells connected in parallel, shall be equipped with effective means to prevent dangerous reverse current flow (e.g., use diodes, fuses, etc.).

6.1.4.1. CID

(Test Plan of Additional Mitigation Measures– No. 3)

CID's are usually inside the cell casing, **Figure 8**. When internal cell pressure exceeds a certain threshold, this device physically disconnects the electrical path between the electrodes and the external poles of the cell. They act as non-resetting circuit breaker. Several components of the CID include a safety valve, an insulating spacer and a thin metal plate that connects to the electrodes in the cell. When gasses build within the cell, the safety valve deforms, thereby causing it to separate from the thin metal plate. Once the safety valve and thin metal plate have separated, the electrode is disconnected permanently from the exterior can and the current can no longer flow.

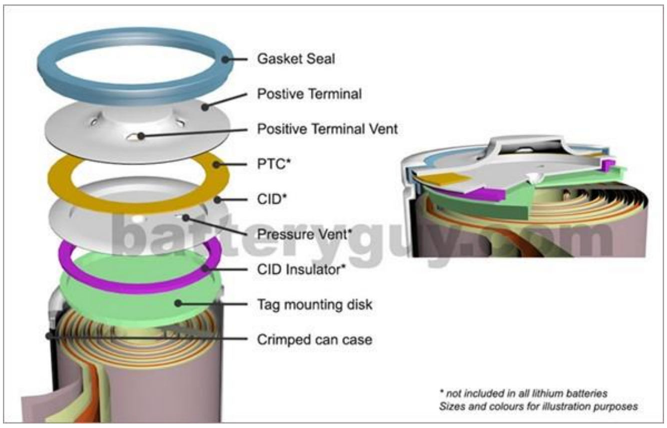

Figure 8: *Diagram of various cell level mitigation measures for a cylindrical format lithium ion cell.* *[*Source: *www.batteryguy.com]*

6.1.4.2. PTC

(Test Plan of Additional Mitigation Measures– No. 3)

Another type of protection device used in LIBs is the Positive Temperature Co-efficient (PTC) resettable current limiter, **Figure 9**. These may be located inside or outside the cell. They provide a reversible current limiting function primarily for low-current applications. They can reset themselves when the over-current condition returns to normal. PTC are resistors with a positive temperature co-efficient, which means that the resistance increases with increasing temperature.

Figure 9: *An example of PTC device.* [Source: *TDK Corporation, Japan]*

6.1.4.3. Cell Vents

(Test Plan of Additional Mitigation Measures– No. 3)
Vents are meant to allow a controlled escape of gases from the cell. **Figure 10** shows a vent for a pouch design cell. These vapours are either due to the heating of the electrolyte organic solvent, or the decomposition of the electrolyte as a result of unwanted electrochemical reactions.

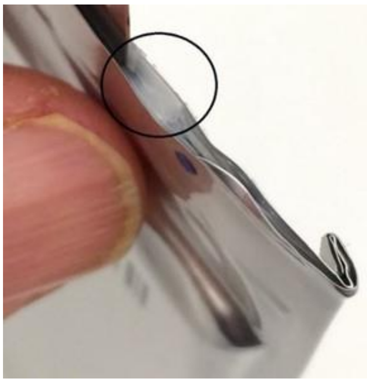

Figure 9: *A vent for a pouch cell is created by inserting a small plastic spacer in the weld between laminate sheets to create a weak point that can rupture as pressure increases. [*Source: *ALGOLiON Ltd.]*

6.1.4.4. Cell Fuse

(Test Plan of Additional Mitigation Measures– No. 3)

Fuses are designed to break the electrical connection between the cell and the external load when the current surpasses a certain threshold. Cell level fusing in pouch cells can be implemented by stamping out holes or slots in the electrode tabs of a certain pattern. As an example, **Figure 11**, the 20 AH cell, the fuse will clear after about 1 second at 1,800 amps.

Figure 10: *A pattern of holes and slots in a pouch cell tab (right side) acting as fuse. [*Source: *A123 Systems, Lt]*

6.1.4.5. Shut-down Separators

(Test Plan of Additional Mitigation Measures– No. 3)

Shut down separators inhibit the flow of current between the electrodes through the electrolyte once a critical temperature has been reached. The high temperature closes their pores.

As a mitigation measure to consider, all separators in cells could be regulated and certified by appropriate bodies as an official shutdown separator. Shipping documents could state among other items that the separator is a certified shut-down separator.

Some LIB separators have a shutdown feature, **Figure 12**. For a typical tri-layer design, the two outer layers have a higher phase transition temperature than the inner [13, 14]. A common design is PP/PE/PP (PP = propylene and PE = polyethylene). The melt temperature of the PE is lower than that of the PP (for example, the Celgard Company has a family of tri-layer design separator products made of PP/PE/PP. The melt point of PE is 134^o C and that of the PP is 166^o C. As the temperature of the cell rises, the PE melts first and fills the pores of the outer PP layers, creating a barrier to ionic current flow and a physical solid separation between the anode and the cathode. Upon arriving at the glass transition temperature, local melting of the polymer causes collapse of the separator's porous structure irreversibly blocking current flow and creating a solid polymeric barrier between the electrodes. However, this mechanism will not work above decomposition temperature of the polymer.

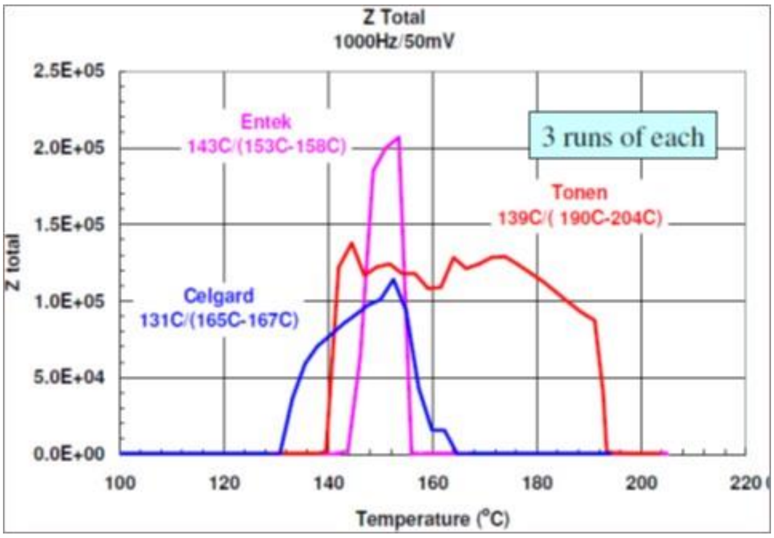

Figure 11: *Shut-down characteristics of separators from various manufacturers; shut down is indicated by a sudden rise in resistance as measured by ac impedance at 1000 Hz. At higher temperatures above shutdown, the separator eventually breaks down (Source: E.P. Roth – Abuse Tolerance Improvement, DOE Vehicle Peer Review (2008)).*

Other solutions based on the separator for protecting the LIB, include coating the separator with a ceramic coating. The purpose is to mitigate against penetration of dendrites. Ceramic coatings have included $LiAlO_3$, alumina, MgO, TiO_2, and $CaCO_3$. Some companies that manufacture such composite ceramic separators include Entek, Celgard, and Degussa. LG Chem is a major battery OEM using ceramic coated separators in lithium ion cells. Other approaches with ceramic include the use of a coating incorporating ceramic powder within the matrix of the polymer. In any case, the use of ceramics appears to improve the thermal stability of the separator but even the most robust ceramic separators cannot stop thermal runaway once it begins.

6.1.5. Events which may Lead to an External Short

(Test Plan of Additional Mitigation Measures– No. 4)

A risk associated with the transport of batteries and battery-powered equipment is external short-circuiting of the battery as a result of the battery terminals contacting other batteries, metal objects, or conductive surfaces. According to IATA [5, 6, 7], methods to protect against short circuit include, but are not limited to, the following methods:

- Packing each battery or each battery-powered device when practicable, in fully enclosed inner packaging made of non-conductive material (such as a plastic bag).
- Separating or packing batteries in a manner to prevent contact with other batteries, devices or conductive materials (e.g. metal) in the packaging.
- Ensuring exposed terminals or connectors are protected with non-conductive caps, nonconductive tape or by other appropriate means.

If the packaging is not impact resistant, then it is recommended not to be used as the sole means of protecting the battery terminals from damage or short-circuiting. Batteries should be securely cushioned and packed to prevent shifting which could loosen terminal caps or reorient the terminals to produce short circuits.

Protection of the cell electrical terminals (positive and negative poles) include the following measures:

- Securely attaching covers of sufficient strength to protect the terminals.
- Packaging the battery in a rigid plastic packaging.
- Constructing the battery with terminals that are recessed or otherwise protected so that the terminals will not be subjected to damage if the package is dropped.

According to ICAO/IATA, [6] cells and batteries must be packaged in a manner that prevents external short circuits, see for example Fig. 16. Moreover, air transported lithium ion cells or batteries must be able to pass UN 38.3.4.5 Test T.5 – External Short Circuit. Additional non- obligated industrial regulation contains the UL 2054, Sec 9 Short-Circuit Test and UL 1642, Sec 10 Short-Circuit Test [13, 14, 15]. These tests replicate a short circuit of the terminals. Terminals of an exemplary prismatic cell are shown in **Figure 12**, pouch in **Figure 13**, and cylindrical **Figure 14**.

Figure 12: *A prismatic lithium ion cell showing exposed positive and negative terminals. [*Source: *DIY Trade].*

Figure 13: *Lithium ion pouch cells: (left) cell individual wrapped in plastic envelope, (right) three such individually wrapped cells in secondary plastic envelope for redundancy. [*Source: *ALGOLiON Ltd.]*

Figure 14: *Lithium ion 18650 cylindrical cells: (left) cells packed with cardboard isolators between each cell, (right) cells packed with no isolators between them. [*Source: *ALGOLiON Ltd.]*

Packaged batteries or cells must be separated in a way to prevent short circuits resulting out of defects ranged from poorly designed or assembled batteries [16, 17, 18, 19] or damage to terminals. They must be packed in a strong rigid outer packagings unless when contained in equipment, in which the battery is afforded equivalent protection by the equipment in which it is contained [16, 17, 18, 19]. Each battery should be packed in fully enclosed non-conductive material which would prevent contact with conductive materials (e.g. metal, other batteries, etc.). Sample packaging meeting these requirements is shown in **Figure 15**.

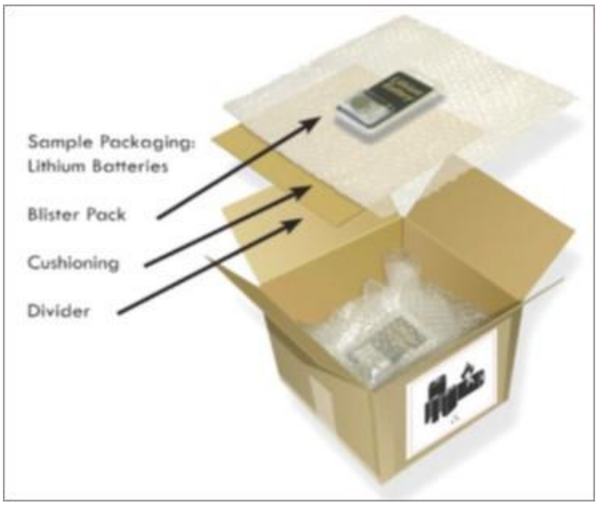

Figure 15: *Example of IATA approved packaging. [*Source: *IATA]*

As a mitigating measure, the cells' exposed terminals or connectors could be protected with non-conductive caps, tape, etc.

6.1.6. Pre-evaluation of battery state of safety with early warning diagnostic software

(Test Plan of Additional Mitigation Measures– No. 5, 12)

Prior to inserting batteries into packaging for transport, some of them, as a quality check, could be evaluated with a predictive diagnostic check for their state of safety. This could be used to identify potentially dangerous cells which would be prohibited from being shipped. In the near term, this check will be performed by the battery manufacturer or a shipper. In the long term, cost effective smart packaging could be developed to monitor the safety of cells with such software diagnostics, and communicate an alert. Section 7 covers an example of diagnostic software methods.

6.1.7. Latency period after cell formation process

(Test Plan of Additional Mitigation Measures– No. 6)

Lithium ion cells undergo a charging process called formation cycling at the end of their manufacture. If an internal fault is present at the time of manufacture, it could be enhanced or catalysed to form an internal short by the formation cycling. In such cases, thermal runaway reactions may occur soon after completion of their formation charging by the battery manufacturer [20, 21]. As a mitigation measure to consider for the transport of freshly manufactured cells, a minimum ‘wait-and-see’ latency period could be defined of at least several days between the conclusion of the formation cycling and air cargo transport to allow for the emergence of cell heating, possibly leading to thermal runaway. This would conceivably be done by the battery OEM at its facility as part of the outgoing inspection checks after formation cycling.

6.2. Packaging Level

(Test Plan of Additional Mitigation Measures– No. 7 to 12)

6.2.1. Thermal Isolation Materials

(Test Plan of Additional Mitigation Measures– No. 7, 21)

Fire-proof/thermal insulation materials can be used to contain propagation of thermal runaway fires. The material can be used as an additional mitigating measure to packaging either inserted between cells within a package, between packaging, or in some cases, coated onto packaging materials.

Based on the specific density, heat capacity and thermal isolation of various electrical isolating materials, [16, 17, 18, 19, 21] the minimum safe distance between cells can be estimated for cases of different types of thermally isolating materials. Presentation of these studies is provided in the Sabatair D2a deliverable report.

6.2.1.1. PyroBubbles®

(Test Plan of Additional Mitigation Measures– No. 7, 21)

This a non-conductive (thermally and electrically 150 µS/cm) extinguishing agent [22] for solid and liquid combustible substances (Class A, B, D and F), see **Figure 16**. The material is porous hollow glass granules. It is very lightweight (approx. 235 kg/m³). The main ingredient is silicon dioxide with an average 0.5 - 5 mm grain size. PyroBubbles® can withstand temperatures up to approx. 1,050° C which makes them resistant to thermal runaway temperatures.

Figure 16: *Pyrobubble ® granule. [*Source*: LiMATECH GmbH].*

6.2.1.2. Mineral Wools

(Test Plan of Additional Mitigation Measures– No. 7, 21)

The D2a deliverable report should be referenced for more information on this material.

6.2.1.3. Phase Change Materials

(Test Plan of Additional Mitigation Measures– No. 7, 21)

A phase change material (PCM) is a substance with a high heat of fusion, see **Figure 17**. The temperature of the PCM rises as they absorb heat. Unlike conventional materials, when PCMs reach the temperature at which they change phase (their melting temperature) they absorb large amounts of heat at an almost constant temperature. The PCM continues to absorb heat without a significant rise in temperature until all the material is transformed to the liquid phase.

PCMs could be a suitable packing agent to consider to limit the temperature rise of a cell. As a passive solution, it lends itself to be used as a possible mitigating means in addition to packaging since its very high phase change enthalpy means only a small amount is needed. Its poor thermal conductivity means it can be used to minimize propagation of thermal runaway from one cell to another.

Figure 17: *Paraffin wax is one type of PCM considered for lithium ion battery applications.* [Source: *Andores New Energy CO., Ltd., China].*

6.2.1.4. Pyrolytic Graphite Sheet (PGS)

(Test Plan of Additional Mitigation Measures– No. 7, 21)

Various companies, such as Panasonic [23], provide PGS sheet, **Figure 18**, solutions for thermal insulation. These sheets are characterized by high heat resistance, insulation and thermal stability. They have a thermal conductivity 2-5 times greater than copper and 3-8 times higher than aluminium. It is ideal for providing heat-sink capabilities.

Figure 18: *Pyrolytic Graphite Sheets are thin and flexible. They are available in either roll or sheet form and be easily cut and shaped for packaging purposes.* [Source: *Panasonic, [23]].*

6.2.1.5. Silica Aerogel

(Test Plan of Additional Mitigation Measures– No. 7, 21)

As an example, Panasonic [23] markets a proprietary nano-silica aerogel and polyester fibre composite sheet, see **Figure 19**. It is provided as a thin, flexible heat insulating material that has high thermal isolative properties. Its thermal conductivity is comparable to that of air, making it a suitable material for heat insulation. The silica is structured into nanoscale hollow particles to provide a highly porous sheet with a thermal conductivity of roughly 0.02 W/m·K. Marketed under the name NASBIS by Panasonic [23], it can provide various counter measures against heat. The range of NASBIS sheet thicknesses is 100µm to 1,000µm.

Figure 19: *example of Nano-silica insulating sheet with polyester fibers. [*Source: *Panasonic, [23]].*

Use of such non-flammable films was proposed in 2012 by the Dangerous Goods Panel Working Group on Lithium Batteries as a means to reduce the risk of fire propagation. However, their use as a mitigating measure was not adopted then. This material is mentioned here in order to provide a comprehensive survey of possible measures to the reader. The material can be applied as a non-flammable film to protect against lithium ion battery packaging catching fire when adjacent to a fire source.

6.2.1.6. Packaging Fire Extinguishing Media

(Test Plan of Additional Mitigation Measures– No. 7, 21)

Extover® is a non-conductive (thermally 0.07W·m^{-1}·K^{-1} and electrically) extinguishing agent [24, 25] made of dry powder (5-18 mesh) consisting of porous (85%) SiO_2 foam glass granules, see **Figure 20**. It is certified to prevent and extinguish lithium ion and metal battery fires. Among its properties are its ability to condense exhausted gas, neutralise hydrofluoric acid (HF), displace oxygen, avoid re-flaming and absorb electrolyte spills.

Figure 20: *Extover fire extinguishing agent. [*Source: *Extover Fire Extinguisher Company, [24, 25]].*

6.2.1.7. Intumescent Materials

(Test Plan of Additional Mitigation Measures– No. 7, 8)

Intumescent materials are substances that swell as a result of heat exposure, therefore increasing in volume and decreasing in density. Intumescent materials are typically used in passive fire protection. Some details are specified in technical standards which are compiled and published by national or international standardisation bodies like the British Standards Institute (BSI), the German Institute for Standardization (DIN), the American Society for Testing and Materials (ASTM) or the International Standardization Organization (ISO). These materials are known for application to lithium ion battery safety such as in US patent 8,263,254 B2, assigned to Tesla which uses these materials interspersed between cells in a pack. The patent covers a battery assembly that includes a layer of intumescent material that coats the sidewall and bottom surface of the cell casing.

6.2.2. Cell rupture

(Test Plan of Additional Mitigation Measures– No. 9)

Cells or batteries with low quality seals, and which are exposed to low pressure at high altitude, may rupture causing electrolyte leakage. Electrolyte leakage should be handled similarly to either flammable gas or a chemical spill. Air transported lithium ion cells or batteries must be able to pass altitude simulation according to both UN 38.3.4.1 Test T.1 – Altitude Simulation, and Test T.2 – Thermal Cycling [4, 15] and IEC-62281. Additional non- obligatory regulations contain the UL 1642, Sec 19 Low Pressure (Altitude Simulation) Test and temperature cycling [15].

6.2.3. Electrolyte and Gas Absorbing Materials

(Test Plan Table – No. 9, 20)

6.2.3.1. Vermiculite

(Test Plan of Additional Mitigation Measures– No. 9, 20)

This is a non-flammable phyllosilicate ceramic (**Figure 21**). Vermiculite is used as an absorbent for chemical spills meaning it may be useful to adsorb any flammable electrolyte leaking from cells.

Figure 21: *Vermiculite. [*Source: *Wikipedia].*

Additionally, Vermiculite exfoliates due to exposure to heat. Similar to popcorn, its absorbed water gains energy when heated and then steams and pops. Upon its significant expansion during the exfoliation, the Vermiculite's specific gravity is reduced from 2.6-2.4 to 0.06 g/cc. The grains of Vermiculite gain significant air layers in this process which makes it excellent for thermal insulation and mechanical cushioning.

6.2.3.2 Sorbix

(Test Plan of Additional Mitigation Measures– No. 9, 20)

This is a non-flammable, non-conductive light weight fine granulated commercial calcined calcium silicate (**Figure 22**) similarly to the Vermiculite. Sorbix can be utilised also as an electrolyte spill absorber which will mitigate electrolyte evaporation and by that preventing its flammable vapours from reaching flammability limits.

Figure 22: *Sorbix granules. [*Source: *RITTER Chemie GmbH].*

6.2.4. Penetration

(Test Plan of Additional Mitigation Measures– No. 10)

Penetration of packages can occur during handling, loading cargo onto the aircraft, in cargo warehouses or in the logistics centres, on conveyor belts or dollies. UN and ICAO/IATA regulations clearly state that dangerous goods packaging must **not** be loaded onto aircraft if they are damaged or leaking. Physical deformation or penetration of packaging containing lithium batteries may result in mechanical damage, as referred to above, which may lead to thermal runaway (instantly or postponed). A mechanically robust overpack used by the shipper may be able to mitigate some of possible damage to cells from penetration, crush, vibration, impact, shock and kinetic fragments. [16, 17, 18, 19]. In cases of a commercial open-sided pallet, it seems almost impossible that mishandling, leading to penetration of the packaging will not be observed by the cargo personnel. In such cases ICAO/IATA forbids the transportation of batteries by air [5, 6, 7].

6.2.5. Impact

(Test Plan of Additional Mitigation Measures– No. 10)

Lithium cells or batteries must be able to pass IEC-62281, UN 38.3 Test T.6 – Impact [4, 7] which will ensure that it will be capable of withstanding a 9.1 kg mass $\pm$ 0.1 kg dropped from a height of 61 cm $\pm$ 2.5 cm.(ICAO Packing Instructions 965, 966, 968 and 969 use 1.2 metre as the criteria for package specification meeting UN packing group II requirements). Additional non-obligatory standards include UL 1642 standard, Sec 14 Impact Test, and UL 2054, Sec. 15 Impact Test.

Improper outer impact resistant packaging must not be used as the sole means of protecting the battery terminals from damage or short-circuiting. Batteries must be securely cushioned and packed to prevent shifting which could loosen terminal caps or reorient the terminals to produce short circuits. In general, this protection is referenced by ICAO Instructions 965-970 which state that *"lithium ion cells and batteries must be protected against short circuit"*. Terminal protection methods include but are not limited to the following:

- a) securely attaching covers of sufficient strength to protect the terminals;
- b) packaging the battery in a rigid plastic packaging;
- c) constructing the battery with terminals that are recessed or otherwise protected so the terminals will not be subjected to damage if the package is dropped [4, 7].

Mitigation measures should include making packaging more resistant to crush, impact, drop, shock and vibration. The standards IEC-62133 and UL 2054 use a criterion of a free fall drop from a height of 1 metre. ICAO Packing Instructions 965, 966, 968 and 969 use 1.2 metres as the height criteria. The ICAO greater height is to take into account conditions that better reflect those normal to air transport. The height used to determine if the cells pass the impact tests could be increased further to reflect the height of:

- Conveyor belts in warehouses and logistics centres.
- Shelves used to store cells in warehouses.

Shelf height has already been examined in practice. However, due to the design of warehouses and conveyor belts in logistics centres, there are many locations where the package of the cells is at a height greater than 1.2 metres. There is no realistic packaging solution for lithium batteries or anything else that can withstand a drop from such height without some damage whether in compliant packaging or not. Note that the regulations already require that no damaged or leaking dangerous goods packages be loaded onto aircraft. Therefore, if a package does experience a drop from heights above the IEC and UL standards height and it is damaged, then as per the guidelines, it will not be loaded onto the aircraft. On the other hand, no information can be gained from inspection of the packaging about what happened to the cells inside of it, which may have been damaged or jumbled in such a way as to create a short between individual cells.

6.2.6. Vibration

(Test Plan of Additional Mitigation Measures– No. 10)

Vibration of boxes and packaging may lead to cell or battery damage resulting in electrolyte leakage, mechanical fracture, short circuits etc. Therefore, batteries/cells need to meet vibration testing standards. Vibration resistant packaging and the arrangement of batteries/cells within the packaging might be able to be developed to reduce the effect of vibration on batteries/cells. Air transported lithium ion cells or batteries must be able to pass IEC-62281 and UN 38.3.4.3 Test T.3 – Vibration [4, 5, 6, 7]. This test simulates vibration that can occur duration transportation. Additional non-obligatory industrial standards include UL 1642, Sec 16 Vibration Test.

6.2.7. Shock

(Test Plan of Additional Mitigation Measures– No. 10)

Air transported lithium ion cells or batteries must be able to pass IEC-62281 and UN 38.3 Test T.4 –Shock [4, 5, 6, 7] and UL 1642, Sec 15 Shock Test. These tests simulate impacts that could occur during transportation or handling of the packaging [16, 17, 18, 19].

6.2.8. Crush

(Test Plan of Additional Mitigation Measures– No. 10)

Crushing of cells or batteries or their packaging may cause electrolyte leakage or short circuit which can eventually lead to heating, thermal runway and fire. UN packaging specifications include a stacking test. Non-obligatory industrial standards include the UL 1642, Sec 13 Crush Test [4, 5, 6, 7]. In order to avoid packaging from being crushed, a mitigating solution to be considered is the use of a hard case enclosure on cardboard or soft walled supplemental packaging.

6.2.9. Kinetic fragments

(Test Plan of Additional Mitigation Measures– No. 10, 11)

Kinetic fragments may be generated from burst cells in a thermal runaway event.

The batteries could be packed in a way that will reduce fragments from a cell or battery penetrating or igniting adjacent packages in the event of an explosion especially cardboard or fibreboard packaging [16, 17, 18, 19].

A mitigation measure to consider, and one that is being reviewed by the G-27 Committee, blankets, relates to covers or fine nets (that will not block the fire suppression and cooling means) for fragment absorption. This could be used as an external layer or internal layer to packaging. According to which the package would be required to prevent the exiting of hazardous fragments that have sufficient energy to pass through or ignite adjacent packages [16, 17, 18, 19].

6.2.10. Fire Resistant Overpack for Packages

(Test Plan of Additional Mitigation Measures– No. 10)

A fire-resistant cover on the cell/battery package applied by the shipper could mitigate hazardous flames, fragments and heating of neighbouring packages from a thermal runaway event in a neighbouring package and from a fire within the covered package.

6.2.11. Minimum Safe Distance between cells

(Test Plan of Additional Mitigation Measures– No. 11)

Another category of passive fire protection is to place cells at a minimum safe distance (MSD) apart within the packaging so that thermal runaway between cells is mitigated. The MSD will depend on the energy of each cell (capacity and SOC), size and format [21].

6.3. Operator Level

(Test Plan of Additional Mitigation Measures– No. 13 to 23)

6.3.1. Heat or Fire Exposure

(Test Plan of Additional Mitigation Measures– No. 13, 14, 19)

In the case of external heating, it was demonstrated that ignition requires severe heating for a significant time (e.g. 350^{o} C, 5 minutes) [25]. Simple thermal isolation (e.g. packaging carton) might also mitigate the combustion of cells [25]. Moreover, by taking into account the low probability of the propagation effect combined with the required external heat, a possible mitigating measure could be to design and engineer a new type of ULD that incorporates a cooling system. This could reduce the effect of external heating on the transported cells or the spread of heat within the cargo compartment due to a fire within the ULD.

The allowed outer packaging materials are:

IA.3 **Outer packagings**

Boxes	*Drums*	*Jerricans*
Aluminium (4B)	Aluminium (1B2)	Aluminium (3B2)
Fibreboard (4G)	Fibre (1G)	Plastics (3H2)
Natural wood (4C1, 4C2)	Other metal (1N2)	Steel (3A2)
Other metal (4N)	Plastics (1H2)	
Plastics (4H1, 4H2)	Plywood (1D)	
Plywood (4D)	Steel (1A2)	
Reconstituted wood (4F)		
Steel (4A)		

According to ICAO Instruction Packaging Instruction 969 non-combustible packaging of cells is required on passenger aircraft for lithium metal cells:

— For lithium metal cells and batteries prepared for transport on passenger aircraft as Class 9:
  — cells and batteries offered for transport on passenger aircraft must be packed in intermediate or outer rigid metal packaging surrounded by cushioning material that is non-combustible and non-conductive and placed inside an outer packaging.

Although out of the scope of this Sabatair project, the following is mentioned by way of reference. According to ICAO and IATA [5, 6, 7], when batteries are contained in equipment, the equipment must be packaged in a manner that prevents unintentional activation or must have an independent means of preventing unintentional activation (e.g. packaging restricts access to activation switch, switch caps or locks, recessed switches, trigger locks, temperature sensitive circuit breakers, etc.).

6.3.2. Fire Resistance of the ULD

(Test Plan of Additional Mitigation Measures– No. 13)

Fire Resistant Containers (FRC) ULDs may be a solution to reduce the threat of lithium battery fires for Class C, E and F compartments. Controlling a fire in the ULD requires the following to be taken into consideration:

- Thermal insulation (reduction of the heat transfer coefficient) to avoid the ignition of the ULD next to the heat source (neither additional lithium batteries nor flammable cargo).
- The oxygen evolution rate from the metal oxide cathode at elevated temperature.
- Avoid contact of dangerous materials released from the fire (e.g. HF, smoke, etc.) with the crew, as is true for any fire on the aircraft.

Mitigation measures can be proposed for consideration as follows. It is noted that some may not be compatible with all types and sizes of aircraft, and could be costly, or not currently available.

- Utilize Fire Resistant Container ULDs
- Add a smoke, fire, vapour, and/or HF detection capability meeting airworthiness regulations into the ULD for faster response and detection of the specific ULD in danger. One could consider redundant systems to avoid false positive readings (e.g combination of heat, smoke or flame detection).
- Automatic extinguishing devices meeting airworthiness regulations within the ULD or penetrators located above each ULD which automatically pierce the roof and deploy a fire extinguishing agent directly into it.
- Cooling and isolating the ULD via severe air flow originating from outside of the plane (ca. -50°C air temperature with high velocity at high altitude).
- A double wall design of the fire-resistant ULD (with or without the air cooling) will provide the required thermal insulation in case of fire next to a pallet.

For a theoretical background based on information from Exponent, Inc. testing laboratories, an open fire of pallet of batteries provides about 5MW of power with a peak of 8.8 MW. This large amount of power is indicative of the danger posed by battery fires.

6.3.3. Shock indicator

(Test Plan of Additional Mitigation Measures– No. 15)

A shock indicator can be considered to be placed on the external wall of the ULD. Its operation would be independent of the certified aircraft system. This would provide an indication to the operator if the ULD experienced an abnormally high physical shock that could have adversely affected batteries inside. This information could be used to exhibit caution when opening the ULD.

6.3.4. Temperature indicator

(Test Plan of Additional Mitigation Measures– No. 16)

Consideration can be given to placing a temperature registration indicator on the external wall of the ULD. Its operation would be independent of the certified aircraft system. This would provide an indication if the batteries within the ULD were subject to excessive temperatures. This situation could occur while a ULD filled with batteries was delayed on the tarmac in hot climates (summer, tropical countries) prior to loading onto the cargo aircraft.

6.3.5. Smoke Detector

(Test Plan of Additional Mitigation Measures– No. 17)

Consideration can be given to fitting ULDs with various smoke or fire detectors such as a smoke alarm. This device would be a redundant system independent of the certified aircraft system that would initiate an automatic mechanical action to supress the starting fire. The detector would also be useful for detecting hazards when the ULD with was no on board an aircraft.

6.3.6. Fire Suppression System

(Test Plan of Additional Mitigation Measures– No. 18)

The fitting of ULDs with automatically triggered, self-contained fire suppression (e.g., Halon, pressurized CO_2, compressed nitrogen) which would be independent of the certified aircraft system can be considered.

6.3.7. Electrolyte and Gas Absorbing Materials

(Test Plan of Additional Mitigation Measures– No. 20)

Using liquid absorbing vermiculite (section 6.2.3.1.) or Sorbix (section 6.2.3.2) inside the package can be considered.

6.3.8. Thermal Insulation Materials

(Test Plan of Additional Mitigation Measures– No. 21, 23)

Using thermal insulation materials thermal insulation materials inside the ULD can be considered. These may include Pyrobubbles® [22] (section 6.2.1.1.), mineral wool (section 6.2.1.2.), phase change materials (section 6.2.1.3.), pyrolytic graphite (section 6.2.1.4.), silica aerogels (6.2.1.5.), fire extinguishing media like Extover® (section 6.2.1.6.) and intumescent materials (section 6.2.1.7.).

6.3.9. Pressure release

(Test Plan of Additional Mitigation Measures– No. 22)

Most container ULDs, including redesigned FRCs, allow for venting to prevent pressure build-up during a thermal event. The location and sensitivity level of such devices could be looked at for optimization.

6.4. Alarm Level

(Test Plan of Additional Mitigation Measures– No. 24 to 27)

6.4.1. Temperature Sensors

(Test Plan of Additional Mitigation Measures– No. 24)

It can be considered to install, within the ULD, a temperature sensor. This could serve for example to trigger an alarm or activate a secondary (on ULD level for example, redundant with the aircraft system) suppression fire system if the temperature exceeds a set threshold, which could be caused by cell heating due to external or internal causes.

6.4.2. Infra-red imaging

(Test Plan of Additional Mitigation Measures– No. 25)

Infra-red imaging, as a sensor for the heat generated by an internal short in a cell, can possibly be used to detect high cell temperatures. The sensor would need to meet airworthiness certification. This may be done via instruments as a pre-flight inspection to detect hot cells (those with a developing internal short and thus exhibiting a higher than ambient temperature) during warehouse operations prior to loading a ULD (for example during x-ray screening). Infra-red imaging equipment could also be installed in the cargo compartment for real-time monitoring of cargo while in-flight. Again, this would allow the system to meet aircraft worthiness certification.

6.4.3. Toxic gas leaking out of a cell into packaging

(Test Plan of Additional Mitigation Measures– No. 26)

The gases released from a lithium battery when burned or leaked have some toxic effects. These effects are not greater than class 2 according to the NFPA 704, i.e. intense or continued but not chronic exposure could cause temporary incapacitation or possible residual injury. An exceptional case is the HF (Hydrofluoric acid) which is defined as highly toxic (class 4 according to the NFPA 704, i.e. very short exposure to a potent dosage could cause death or major residual injure). Moreover, the toxicity of the emitted gases resulting from thermal decomposition of cell components (e.g. decomposed polymers, smoke, etc.) are of concern.

One of the highest concern materials is hydrofluoric acid (HF). While toxicity is not a cause for banning batteries on aircraft, if released in large amounts from a multi-battery fire it could be chemically damaging to the aircraft and ULD, and residual fumes could be of concern when the cargo compartment is opened upon landing. Based on the current knowledge, an HF detector that meets aircraft worthiness certification requirements could be installed with an alarm set at a HF TLV (Threshold Limit Values) of 0.5 ppm. Where and by whom will need to be determined. HF detectors are not particularly expensive, and their use is widespread in certain chemistry laboratories and in the chemical industry.

6.4.4. Flammable gas leaking out of the cell into packaging

(Test Plan of Additional Mitigation Measures– No. 27)

About 25% of the material content in the cell is flammable (mainly aliphatic compounds and hydrogen) volatile organic compounds (VOC) [13, 20]. These gases can leak or be released from the cells due to various causes during use, misuse or abuse. Based on [13] and [20] a direct relation was found experimentally between the state of charge (SoC) of the cell and the amount of emitted flammable gases- a higher SoC leads to higher gas amount. Therefore, the regulation to limit the SoC of cells transported by air to 30% is supported on this account, as well as reducing its energy content.

Considering this and that a fraction of the gases released are flammable gases (e.g. ethylene, propylene, etc.), and the vapour pressure of the electrolyte (referring to its flammability and explosion limits including the total flammable ingredients), it could be considered to install in the cargo compartment a VOC detector that meets aircraft air worthiness certification. VOC detectors are not particularly expensive, and their use is widespread in certain chemistry laboratories and in the chemical industry. While VOCs are not a cause for banning batteries on aircraft, if released in large amounts it could be of concern when the cargo compartment is opened upon landing.

The Nexceris Company produces an off-gassing sensor for specifically for the detection of lithium battery hazards under the trade name Li-Ion Tamer: https://liiontamer.com/, **Figure 23**.

Figure 23: *One type of commercial VOC detector. [*Source: *Nexceris, USA].*

A related mitigation measure, for redundancy (as is typical in the aviation industry) on the issue of elevated pressure in the cargo compartment, could be the installation and use of a VOC detector that meets airworthiness certification requirements to monitor in the cargo compartment the accumulation of organic vapours.

One technology for a VOC detector is a photoionization detector (PID) which measures volatile organic compounds and other gases in concentrations from sub-parts per billion to 10,000 parts per million (ppm). The photoionization detector is an efficient and inexpensive detector for many gas and vapour analytes. PIDs produce instantaneous readings, operate continuously and are widely used in military, industrial and confined working facilities for health and safety.

In order to reduce corrosion or other material degradation because of the organic vapour, a high surface area material with proper surface suitability for electrolyte absorption (e.g. active carbon) may be added to the packaging or/and installed in the cargo deck with forced ventilation. The SAE G27 standard committee is setting a packaging standard aiming to mitigate the risks which might arise from a failure of an individual cell by containing the hazards within the packaging. According to which the package is required to prevent exit of Hazardous Quantity of Flammable Vapour [16, 17, 18, 19].

In the case of a flammable gas entering a package, one could consider the following as mitigation measures:

- The pallet will have a spill containment feature.

- Use of an absorbing material in the packaging (e.g. treated active carbon, vermiculite) that will reduce the quantity and availability of flammable gas or its liquid phase at levels below its flammability/explosion concentration limit.

6.5 Compartment Level

(Test Plan of Additional Mitigation Measures– No. 28 to 30)

6.5.1. Convert Class E Compartments to Level of Class C

(Test Plan of Additional Mitigation Measures– No. 28)

It is possible, in principle, to convert a class E cargo compartment into class C. This approach would require changes in lining and the installation of a fire suppression system. Since the class E main deck cargo compartments of freighter aircraft are usually of significant bigger volume than any lower deck cargo hold, a related much higher mass of fire suppression agent would have to be stored. This has been considered in the past, nevertheless not passed cost/benefit analyses.

With respect to a class C conversion it could be more realistic to introduce containers in a class E main deck, which provide class C capabilities in terms of burn-through, fire detection and suppression.

6.5.2. Prohibit Transport of Lithium Batteries in Existing Class E Compartments

(Test Plan of Additional Mitigation Measures– No. 29)

The transport of cargo containing lithium batteries in the upper deck Class E compartment of cargo planes as they are presently outfitted could be considered A cost-benefit analysis could shed light on the practicality of such a mitigating measure.

6.5.3. Elevated Gas Pressure in the Cargo Compartment

(Test Plan of Additional Mitigation Measures– No. 30)

The release of gas from cells or due to combustion events may increase the pressure in the cargo compartment. The quantity of flammable vapour must be less than the amount of gas and that when mixed with air and ignited, could cause a pressure pulse in a 2.83 m^3 volume that could dislodge the overpressure panels of the compartment or damage the cargo liner. The calculated pressure is 3.45 kPa [34]. Based on ideal gas law calculations, this means that the amount of gas cannot exceed 4 moles at 25°C or 2 moles at 300°C. By way of example, diethyl carbonate (molar weight of 118 g/mole) which is a solvent used in some lithium battery electrolytes, upon decomposition will provide 1.4 moles of CO_2 and H_2O. As a rule of thumb, the electrolyte represents about 10% of the weight of a cell. In light of the work of the G-27 standard committee, it might not be needed to limit the maximum number (or equivalent weight) of cells that can be packed into a cargo compartment so as not to exceed the allowed pressure increase in the worst case scenario of all cells venting due to fire.

6.5.4. Cooling

(Test Plan of Additional Mitigation Measures– No. 30)

Based on common 18650 cell components, its chemical energy potential at combustion is approximately 280 KJ per cell [13, 20] and added to this is its electric energy up to 40 KJ per cell. A pallet of ten thousand 2 Ah 18650 cells (approximately 20,000 Ah of capacity) would contain approximately 2-3 GJ of energy that could be released by the cells alone. Addition of the packaging material may be significant. For example, the energy content of the batteries associated with notebook computers and its packaging was less than 10% of the overall energy content [13, 20]. This calculation was verified experimentally in the literature and shown that both the heat flux and temperature were mainly controlled by the packaging materials [13, 20].

Thermal runaway caused by an internal defect, of which an internal short from lithium or copper dendrites occurs inside lithium ion batteries and fires derived from them, cannot be extinguished as all the components for the fire are contained within the cell casing:

- Heat generated from the internal short circuit.
- Flammable materials such as organic electrolyte solvents, polyolefin separator, and graphite in the anode and carbon conductive additives in the cathode.
- Oxygen released from the metal oxide cathode.

This means that all the three elements are present inside the cell that are required for the fire triangle. Thus, external extinguishing measures cannot prevent thermal runway in the cell. However, propagation of thermal runaway heat, fire and explosion effects to surrounding cells and the packaging have to be suppressed.

6.5.5. Class C Cargo Compartment Fire Suppression

(Test Plan of Additional Mitigation Measures– No. 30)

Suppressants shown to be effective for suppressing fire propagation outside of the cell include inert gas and other smothering media, like Halon. Smothering is effective in preventing flaming but will not cool cells. Carbon dioxide (Exponent company typically uses carbon dioxide extinguishers to suppress flaming of cells during testing) will not cool cells and prevent thermal runaway propagation. Halons [3] have better suppressant capabilities than carbon dioxide but still lack the cooling capability.

The smoke detection systems installed in cargo compartments of large aeroplanes must provide a visual indication to the flight crew within one minute after the start of the fire. The emergency procedure foresees the immediate manual activation of the Halon-based built-in fire suppression system inside the affected C Class compartment. The time from activation of the semi-automatic fire suppression system to the creation of a fire knock-down effective concentration inside the affected compartment varies depending on aircraft and cargo compartment from 1-2 minutes, where 2 minutes is the accepted maximum. The compartment construction materials are designed to hold the elevated heat (due to the fire) for 5 minutes.

The time line is (1) 1 minute for the smoke detection system to detect a fire, (2) the reaction time of the crew is not specified, and (3) a maximum of 2 minutes from pressing the activation button up to the creation of a knock-down effective concentration inside the compartment.

CS-25 requires ventilation inside a Class C or Class E cargo compartment to be shut off upon detection of a fire. Ventilation may increase rather than reduce the severity of the fire.

7. Diagnostic Algorithms as an Additional Mitigating Measure

Predicting in advance a likely fire in a battery being transported by air may be able to contribute to improved safety. The move towards prognostics / predictive diagnostics is recognized by the SAE's Industry Technology Consortia (ITC) via Recommended Practice JA 6268.

JA 6268 is an aerospace and automotive Recommended Practice (RP) entitled "Design and Run-Time Information Exchange for Health-Ready Components." A "health-ready" component is a supplier-delivered part or sub-system that is enhanced, perhaps with a monitoring system or sensors, to report on its health, or in this case, the state of safety of a battery.

The objective of prognostics is to shift from detecting an actual hazard (and then taking mitigating measures to minimize its consequences) to preventing them in the first place. This can be achieved by using analysis of real-time data. Detection of failures after they occur or just about when they occur, would be replaced by predicting them well enough in advance so that preventive measures can be taken to avoid the hazard all together. The prognostic prediction is meant to identify a benign defect while the item, in this case a battery, is still in a safe condition.

Determining when a battery, manufactured for safe, long life, is close to becoming hazardous is not easy and means that its state of safety should be checked frequently. This is because when thermal runaway in a lithium rechargeable battery may occur is unknown. A real time safety assessment would provide a benefit for improving safety.

ALGOLiON has developed an early warning diagnostic software for lithium batteries [26] that provides safety alerts well before a hazard so that measures can be taken to prevent a fire. The software analyses the normal current and voltage signals of the batteries. Changes in the chemistry of the battery that represent developing precursors to internal shorts and other defects are reflected in small changes in the electrical signals when the faults are still in a safe state. Special algorithms calculate the quantitative values of these parameters and track their changes. In this way, the predictive diagnostic software detects in real-time, up to a week before they occur, any impending failure while battery operation is still within a normal, safe condition. No artificial intelligence nor training sets are required. The method is applicable to all lithium rechargeable chemistries – lithium ion and lithium metal, form factors and cell sizes.

Within Sabatair, the method has been demonstrated to predict thermal runaway induced by external heating significantly before it occurs. The testing was performed in Task 2 and Task 3 of the project.

It is foreseen, that initially one possible way to apply this method for air transport could be to screen batteries before they are packed. The software will be integrated into a purpose-built measuring instrument for testing batteries. Batteries identified as dangerous will not be transported. In the long term, it can be envisioned that development work can engineer smart packaging to monitor batteries during actual transport. If a battery starts to become dangerous then an early warning alert would be transmitted. Appropriate mitigation and preventive measures can then be taken.

7.1. Early Warning Diagnostic Software

In addition to temperature measurements and visual observations, smart diagnostic algorithms may be used to examine electrochemical developments that are precursors to thermal runaway. The software has been developed by ALGOLiON for early warning notification of impending thermal runaway events. The algorithm’s prognostic capability has already been verified in tests at TUV Sud in Munich for nail penetration and crush tests. These studies demonstrated that the parameters generated by the algorithms provide information about developing short circuits significantly prior to a thermal runaway event caused by these abuse tests. The application in the Sabatair project will be the first use of the software for fire testing.

The technology is being studied in Task 2 and Task 3 of the Sabatair project as a means for providing information to optimize mitigating measure to prevent hazards from the air cargo transport of lithium batteries.

7.2. Brief Description of the Technology

ALGOLiON is developing early warning diagnostic algorithms and IT data analytics using mathematical models, artificial intelligence and electrochemical equations to prevent lithium ion batteries from catching fire due to internally developed defects (PCT WO 2017/006319, Israel patent 239,852, various pending patent applications). The algorithms provide the earliest diagnosis of developing internal defects (up to a week) before they may catch fire. This contrasts with existing methods based on hardware or sensors that not only add weight and cost to the system but provide notifications of an impending fire too late to prevent it only seconds before the hazard erupts. The early warning capability is the first to provide sufficient time to optimally manage prevention of thermal runaway.

Figure 25 shows the progression over time of cell temperature in a cell with an internal short. Once the threshold for thermal runaway is reached, the temperature can rise within a matter of seconds to over 700 degrees C. Thus, it is important to diagnose the problem in the early time domain well before the threshold for thermal runaway.

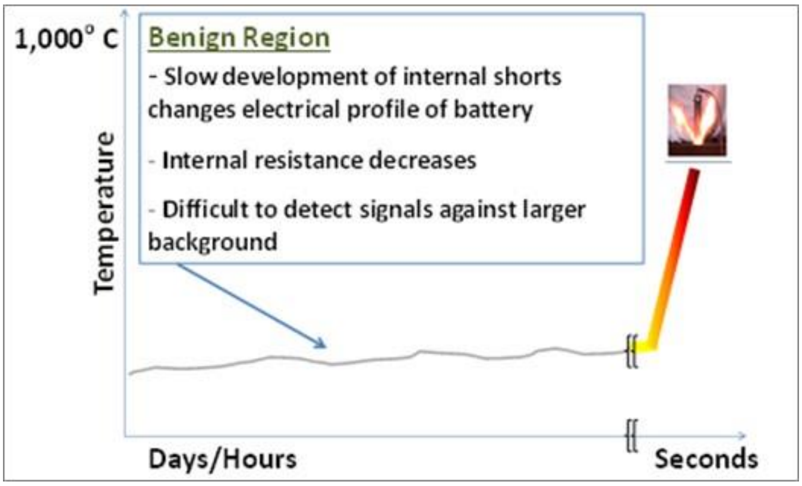

Figure 24: *Progression over time of an internal soft short to a hard short that leads to thermal runaway fire and explosion. [*Source: *ALGOLiON Ltd.]*

The algorithms evaluate the normally monitored voltage and current of the battery and then analyses them according to proprietary software to obtain a set of parameters sensitive to precursors of defects that are not accessible using conventional hardware monitoring techniques.

The derived parameters are at least five times more sensitive to cell degradation than markers from conventional techniques. The ALGOLiON algorithm derived parameters change at a faster rate and by a factor of up to 9x their initial value, depending on the conditions of the cell, which is five times more sensitive than the standard measurements of ac impedance and dc resistance which change by a factor less than two, **Figure 25**.

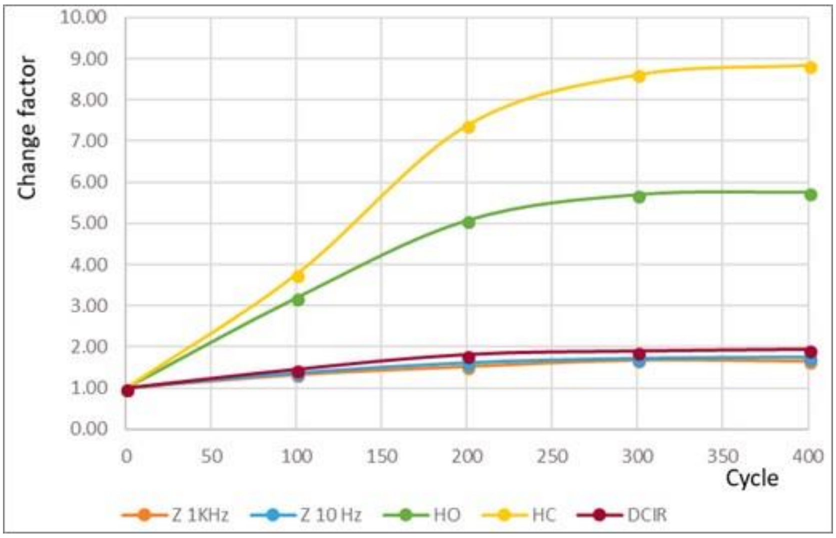

***Figure 25:** ALGOLiON algorithm derived parameters HO and HC compared to conventional markers of ac impedance at 1 kHz and 10 Hz, and dc-iR resistance.* [Source: *ALGOLiON Ltd.]*

The high sensitivity of the technology is achieved with unique methods which provide pivotal parameters, not detected with other techniques, associated specifically with precursors for thermal runaway internal shorts. The software monitors cell current and voltage and then processes these signals to detect changes in electrochemical properties indicative of an internal fault.

<u>Resolution of signals to the individual anode and cathode level:</u>
One of the distinguishing, beneficial features of the technology is that it includes a technique for separating the monitored full cell current and resolves changes in the signal into electrochemical events occurring at the individual anode and cathode. Changes in the signals are indicative of changes in electrode active area. Changes in electrode area, porosity, tortuosity and structure occur during regular use due to extended cycling and more acutely in abuse conditions when early precursors of lithium and copper dendrites grow on the anode surface leading to an internal short and unwanted consequences including thermal runaway. In contrast, the conventional methods are not sensitive enough to resolve the cell signal into contributions from the individual electrodes.

Coupling the parameter indicative of changes in electrode area with the EMS parameter for electrode material and structure is a powerful early warning diagnostic tool for identifying precursors of internal defects in the benign state well before they may reach the thermal runaway threshold.

<u>Early time domain component within a multi-layered approach to battery safety:</u>
The early warning algorithm can be integrated with existing safety management systems in a multi-layered approach. This work ties in with the aviation industry's requirements to adopt improved ways to reduce potential safety hazards of lithium ion batteries in aircraft and to comply with the ever-stricter regulations concerning safe transport of batteries. For both reliability and redundancy engineering, battery safety management

systems, especially in aircraft, may use a multi-layered approach for monitoring battery safety. The ALGOLiON system can be used as one layer providing diagnostics in the early time domain, **Table 3**, of a developing cell fault that can be integrated with other mid- and later time domain methods to create an enhanced comprehensive system.

Technique	Advance Warning Period, Hours
ALGOLiON smart diagnostic software	**120 - 192**
Strain sensor	**0.3 - 1**
Acoustic sensor	**0.2 - 0.5**
ac impedance	**0.1**
Off-gassing sensor	**0.05 - 0.5**
Temperature sensor	**0.01 - 0.1**

Table 3: *The time prior to the start of thermal runaway when various methods provide alerts. [*Source: *ALGOLiON Ltd.]*

7.3. Scientific Basis of ALGOLiON's Algorithms

Since the protocol tracks a suite of signals, several distinct markers are compared for consistency to avoid false negative / false positive readings. The ALGOLiON protocols have been verified in laboratory tests on a variety of different kinds of commercial off-the-shelf lithium ion cells in cylindrical, prismatic and pouch geometries. Cells were conditioned to create proxy shorts. The algorithms demonstrated at least an order of magnitude greater sensitivity to internal cell faults than state-of-the-art techniques like ac impedance and skin temperature monitoring, **Figure 26**.

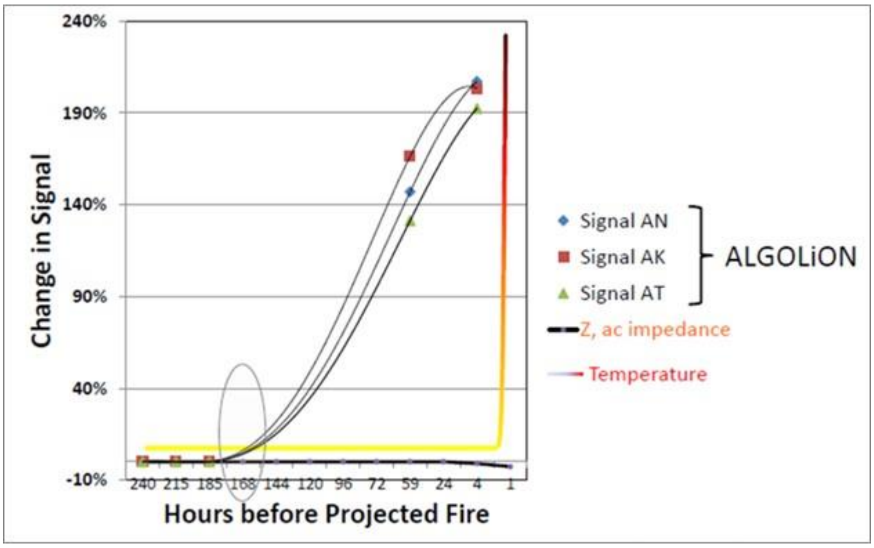

Figure 26: *Increase in three ALGOLiON parameters begins about 1 week before temperature and ac impedance change near the threshold of a simulated thermal runaway event. [*Source: *ALGOLiON Ltd.]*

The algorithms have also been tested by the recognised international certification laboratory TUV Sud in Germany and shown to be able to predict impending cell explosions. In testing where cells were driven to fire events via nail penetration and crush procedures, the algorithms reacted to changes in the cell significantly prior the fire event. **Figure 27** and **Figure 28**.

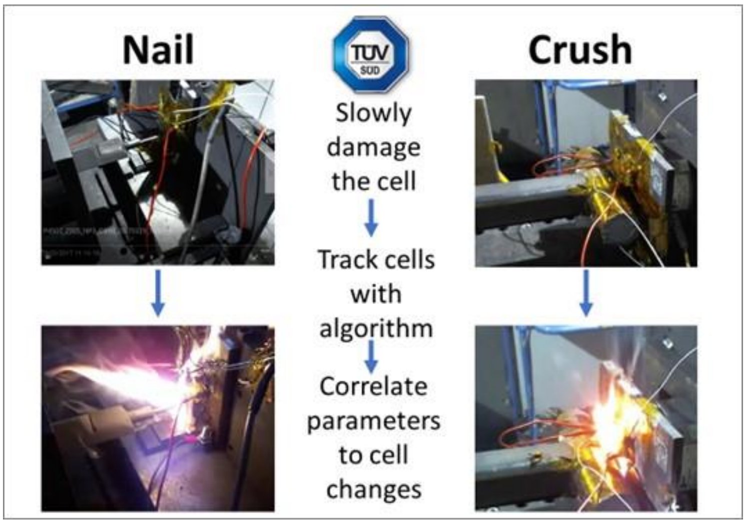

Figure 27: *During the gradual penetration of a nail in the penetration test (left side) or bar in a crush test (right side) on an 18650 cylindrical lithium ion cell, the ALGOLiON algorithm is applied in order to track changes in cell behaviour as the damage to the cell progresses. [Source: ALGOLiON Ltd.]*

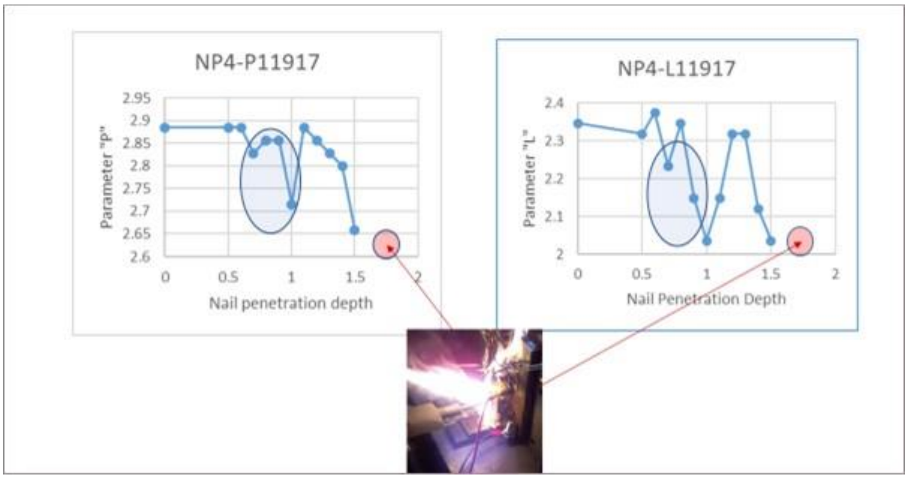

Figure 28: *Changes in two ALGOLiON parameters demonstrating their high sensitivity to progressive mechanical damage due to nail penetration. The parameters show significant change prior to the threshold of thermal runaway.* [Source: *ALGOLiON Ltd.]*

7.4. Implementation of ALGOLiON Diagnostics to Sabatair Testing Program

The first phase of testing in Sabatair will be according to the G-27 Committee Battery Packaging Test Protocol. **Figure 29** shows the basis for the experimental set-up.

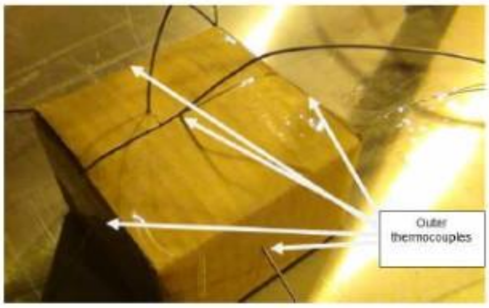

Figure 29: *Thermocouple wires protruding from the test packaging of cells. The wires for the ALGOLiON testing will be adjacent to the thermocouple wires to minimize penetration points in the packaging.* (Source: *SAE G-27 Committee documentation)*

During controlled tests to promote thermal runaway, the ALGOLiON early warning diagnostic algorithms can be applied to a cell via the electrical connections. This can provide information about in what manner sensitive, pivotal electrochemical parameters of cells change during initiation and then propagation of a thermal runaway event within the packaging. The information provides critical knowledge to understanding how to engineer optimised packaging solutions and mitigation measures to be used in addition to the packaging solution.

To evaluate the algorithm under conditions relevant to the Sabatair project, thermal runaway tests based on G-27 procedures were performed in Task 2 at Impact Solutions in December 2018 in cooperation with ALGOLiON. Similar tests are on-going in Task 3 at ALGOLiON.

The general experimental set-up is shown in **Figure 30**. In these tests a single 18650 LG MH1 model cell at 30% SOC was used. The cylindrical heating element was located at the base of the cell.

Figure 30**:** Left side – LG MH1 cell with heating element at base; Right side – heating test chamber at Impact Solutions.

A demonstration measurement instrument built by ALGOLiON was used in the tests to accumulate and analyse the data with associated computer graphic user interface as shown in **Figure 31**.

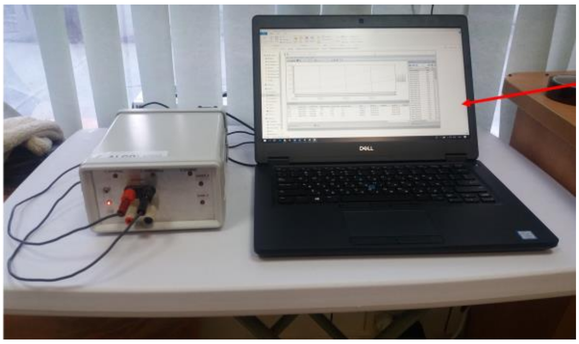

Figure 31*:* Demonstration algorithm data acquisition and measurement box with graphic interface on computer, which includes the data storage

The cell was heated until thermal runaway. The ALGOLiON algorithm monitored the cell continuously during the heating process and calculated various parameters including an 'EMS' parameter for tracking changes in the electrode material and structure. Conventional dc resistance was also recorded. As shown in **Figure 32** the cell went into thermal runaway after about 45 minutes of heating. The conventional dc resistance did not significantly change during this time meaning that it is not a sensitive parameter for predicting a safety hazard. In contrast, the algorithm EMS parameter showed a very large change in value after only about 10 minutes of heating, about 35 minutes prior to thermal runaway. This indicates that it can be considered as a good predictor for eventual safety hazards.

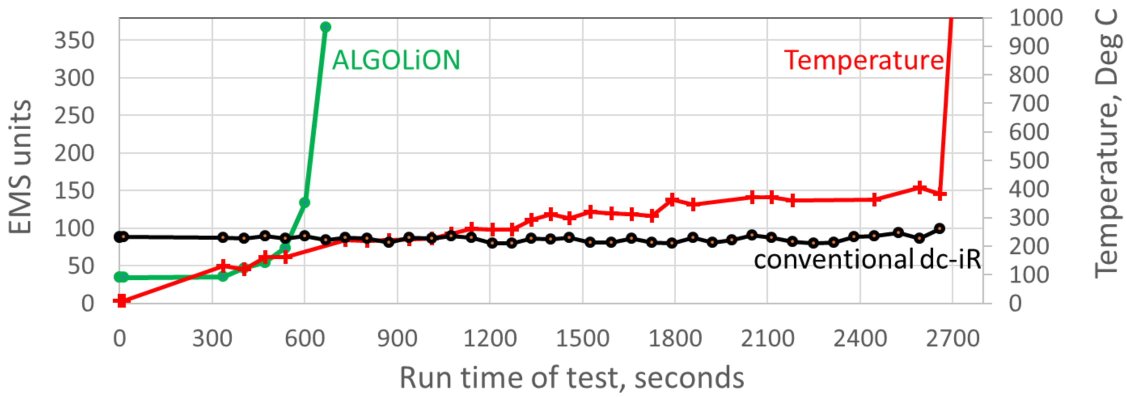

Figure 32**:** Test that induced thermal runaway via cell heating. The test cell was a LG MH1 18650 type with the heating element located at its base. The graph shows as a function of time the heating element temperature, dc resistance of the cell and the ALGOLiON algorithm EMS parameter.

Spatial information within a box of cells can be obtained by applying the algorithm to the initiator and neighbouring cells. Data regarding both the propagation of the fire and the effect of an external fire on the spread of the hazard within the packaging can be obtained. An assessment can be made regarding how cell packing topologies affect the propagation of the fire and how might the propagation be affected by cell size, form factor and chemistry.

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Appendix A

Test Plan of Additional Mitigation Measures

A comprehensive Test Plan of Additional Mitigation Measures to Packaging is provided as this Appendix. The Table is in Excel format and so is provided as an accompanying file to this report. The Table is an integral to part of this report.

The Table lists 35 mitigation measures identified in Task 3. In coordination with the Scientific Committee and EASA, 17 of these were extracted as chosen to be worthwhile to test. The measures identified as those that would benefit from testing were further categorized as high, medium or low priority and whether they would be tested within the framework of Sabatair or otherwise considered. For each of the 35 identified possible measures, the Table lists items including the target level of the measure, the cause of thermal runaway that is mitigated, the consequence of thermal runaway that is mitigated, its technology readiness level and commercial availability, who the measure would affect in the air cargo transport ecosystem and the estimated potential to work and not be circumvented.

Appendix B

Cargo Aviation Real Events Involving Smoke, Fire, Extreme Heat or Explosion Involving Lithium Batteries or Unknown Battery Types

The US FAA Office of Security and Hazardous Materials Safety has compiled a list of events for cargo and passenger plane air/airport incidents involving lithium batteries transported as cargo or baggage. 206 such events have been recorded since from March 20, 1991 to May 2, 2018, 2018 [1]. The present rate of aviation safety events from lithium batteries has now reached an alarming rate of 5 per month. The list below summarizes only the cargo events.

2/14/2018	Airline	Li-ion	Samsung cell phone	FedEx	Cargo	A package containing a cell phone was seen emitting smoke while on the conveyor system at the Memphis sort facility. The fiberboard box was punctured by the sort system and appears to have damaged the phone causing it to go into thermal runaway.
1/30/2018	Airline	Li-ion	MaxAmp 6000XLmah LiPo 11.1v True 100c	FedEx	Cargo	A package containing three batteries was reported as burned prior to loading at the sort facility in Memphis, TN. Fire Services responded and extinguished the fire. Damage was limited to the package and its contents.

12/22/2017	Airline	Li-ion	Solar bank chargers	UPS	Cargo	At SDF, (Louisville, KY) a package containing solar bank chargers with lithium ion batteries, UN 3480, installed was discovered on fire during the loading process.
12/20/2017	Airline	Li-ion	e-cig spare battery	ABX	Cargo	At SEA (Seattle, WA) a package containing 120 suspected Lithium Ion batteries for Vape devices was discovered by DHL employees to be emitting a burning smell. The shipment was tendered in a fiberboard box that had a lithium battery handling label affixed to the. The box was removed from commerce, opened by DHL, and subsequently opened. Numerous battery were found to be damaged or charred. It is not clear when or where the incident occurred as it was discovered after two flights at its final destination airport. After further investigation it was determined that one battery in the box had gone into thermal runaway and the packaging of the other batteries was charred.
11/30/2017	Airline	Lithium (unknown type)	Unknown	FedEx	Cargo	At the Memphis sort facility a package containing an unknown item containing rechargeable lithium batteries was hung up, dragged by a conveyor belt system, and caught fire. The units inside the package were severely damage.
8/18/2017	Airline	Li-ion	cell phones	UPS	Cargo	A package was found to be warm to the touch and smelling of smoke. Inside the package was 20 cell phones, all packaged individually in the manufacturer's box with a battery and other accessories. When the package was opened, UPS personnel discovered a battery for 1 of 20 cell phones had heated to the point of charring the packaging and had began to burn two other cell phone boxes.
7/22/2017	Airline	Li-ion	Power pack/charging device	FEDEX	Cargo	The shipment was found in a FedEx ULD emitting smoke. The box was removed from the ULD, placed in a steel salvage drum & removed from the building. Upon opening the unmarked, labeled box, several lithium ion battery chargers wrapped in clothing were found. There are visible char markings on the chargers themselves and the retail boxes they were in. Four of the chargers were left in the on position and FedEx personnel could not turn them to the off position. The FAA was notified, and the freight was held pending an FAA inspection.
5/2/2017	Carrier	Li-ion	Laptop Computer	FedEx	Cargo	A shipment of 13 boxes of laptops in a cargo facility was inadvertently bumped resulting in one box falling to the ground. Upon impact, the box began to smoke and apparently produced a dangerous evolution of heat. The box and the laptop inside were charred and partially melted. The box contained a laptop computer with a 94 watt-hour lithium-ion battery installed in it.
4/13/2017	Carrier	Li-ion	Unknown	FedEx	Cargo	FEDEX reported that a shipment containing lithium batteries was inadvertently dragged by a dolly until its contents exploded. Investigation is ongoing.
7/21/2016	Carrier	Li-ion	Spare batteries for cell phone	FedEx	Cargo	FedEx reported that a package was found smoking in the sort facility in Memphis, TN. The package was removed from the sort, and once removed it burst into flames. The fire was extinguished, and no injuries or damage was reported. The shipper is from the Santo Domingo and the package was being shipped to Calf. The paperwork for the shipment reflected spare cell phone parts. FDEA reported that the package contain several lithium ion batteries. The package was heavily damaged, so it was unknown if a handling label was on the package
4/3/2016	Carrier	Li-ion	electronic equipment	Kalitta Air	Cargo	1 box of 43 boxes in Cargo shipment of atomization devices w/ lit-ion batteries began to smoke during loading- entire shipment was removed from aircraft and brought to cargo warehouse. Fire department was called and submerged them in water. Many of the devices had lights on them indicating they were "on".

9/15/2015	Fire Dept	Lithium-ion	Multistar 8.0 High Capacity Multi-Rotor Battery	FedEx	Cargo	The Pittsburgh, PA airport fire department responded to a report of a burning package, which was determined to be a USPS package transported from an unknown flight to the cargo facility by a Worlwide cargo runner. Significant burning and damage to the contents, which included numerous li-ion battery packs each containing 4 cells.
7/10/2015	Carrier I-2015070411	Lithium-ion		FedEx	Cargo	Smoke observed from package during sorting at Bangladore, India. No further information available at this time.
5/6/2015	Carrier E-2015050080	Lithium-ion	N/A	Polar Air Cargo Worldwide, Inc.	Cargo	During offload of the aircraft at Leipzig, Germany, onto the belt loader one (1) of eighty (80) packages from a single shipment containing lithium batteries began to smoke. The Fire Brigade extinguished the package on the ramp. The remaining shipments were inspected and checked with a temperature entropy camera, which revealed no signs of heating.
2/13/2015	Carrier	Lithium-ion	N/A	FedEx	Cargo	While loading a FedEx Express aircraft in Bend, Oregon, smoke was seen coming from a unit load device being loaded onto the aircraft. A package inside the container was smoking. This package contained undeclared hazardous materials (lithium ion batteries) having no dangerous goods markings, labels or other indicia communicating the hazardous nature of the cargo.
2/25/2014	DOT 5800.1 Form No E2014020367	Lithium-ion	E-cigarettes	DHL	Cargo	Report from DHL of an international shipment that originated in Hong Kong. It was discovered damaged by fire at the Erlanger, KY sort center. The shipment contained 25 E-cigarette devices, which were enclosed in bubble wrap packagThe contents and packaging were discovered charred and melted. The shipping documents provided inaccurate information about the contents. The package and contents were so damaged it was not possible to establish if the devices were equipped with an effective means of preventing accidental activation. The remaining pieces of the package were removed and stored by DHL. (revised 2/10/2015)
1/21/2014	DOT 5800.1 Form No I2014010428	Lithium-ion	N/A	FedEx	Cargo	Report from Federal Express of an undeclared shipment containing eleven 8 volt lithium-ion batteries that were shipped from Mumbai, India to Sydney, Australia. During processing at the sort center, the shipment was being reviewed by Indian officials when they noted it was extremely hot. When officials separated the package they noted smoke and upon opening the shipment one of the lithium-ion batteries became engulfed with flames. A Security Guard on duty immediately extinguished the flame. The remaining pieces in the shipment are being kept at an isolated location within the Federal Express facility.
10/27/2013	DOT 5800.1 Form No I20113110194	Lithium-ion	N/A	FedEx	Cargo	Report from Federal Express of a shipment containing 174 individually packaged lithium-ion batteries destined for Anchorage, AK. During handling at the Memphis, TN sort facility a single battery was damaged by a dolly. This caused the battery to short circuit and smolder. An employee noticed smoke emitting from the package and reacted immediately with a fire extinguisher. No other damage occurred. The shipper was notified and the remaining contents were shipped without incident.
10/2/2013	DOT 5800.1 Form No 12013100468	Lithium-ion	Lap Top	FedEx	Cargo	Report from Federal Express of a lap top that was damaged by a dolly during handling and caught on fire. The incident occurred at the Memphis, TN sort facility. The battery was removed, and the lap top returned to the shipper.

6/28/2013	DOT 5800.1 Form No I2013070459	Lithium-ion	N/A	FedEx	Cargo	Report from Federal Express of a metal case containing two lithium-ion batteries and 12 aerosol cans that were found to be emitting a strong burning smell. The terminals from one or both of the batteries came in contact with the aerosol cans or each other, which likely resulted in a short-circuit creating enough heat to singe a portion of the package. The shipment was discovered at the Indianapolis, IN facility.
6/27/2013	DOT 5800.1 Form No I2013070217	Lithium-ion	Battery Chargers	UPS	Cargo	Report from UPS of a shipment, which was emitting smoke during the sort process at the Ontario, CA facility. The shipment contained battery chargers with lithium-ion batteries. Several batteries had overheated and appeared charred. The items were placed in a 55-gallon drum and taken to a disposal area.
5/18/2013	DOT 5800.1 Form No I2013050356	Lithium-ion	N/A	DHL	Cargo	Report from DHL Express indicated that two of four boxes in a smoking shipment at their Erlanger, KY facility contained equipment installed with lithium ion batteries that showed evidence of fire.
3/28/2013	DOT 5800.1 Form No I2013040388	Non-spillable, electric storage	N/A	FedEx	Cargo	Report from Federal Express indicated that one of eight packages in a shipment containing undeclared batteries was on fire and another two showed evidence of burning at its Memphis, TN sort facility.
10/27/2012	DOT 5800.1 Form No I2012120190	Lithium-ion	N/A	FedEx	Cargo	Report from Federal Express indicated that a shipment loaded for an outbound flight at its Memphis, TN facility was smoking. The shipment was found to contain 52 undeclared AA ion batteries housed in a box that was burned.
6/7/2012	DOT 5800.1 Form No I2012060342	Lithium-ion	N/A	UPS	Cargo	Report from United Parcel Service indicated that at its Louisville, KY facility, a package containing 18 approximately 1 ounce lithium ion batteries from 6 various manufacturers melted through their plastic wrap causing the outer package to start burning.
4/22/2012	DOT 5800.1 Form No I201240360	Lithium-ion	N/A		Cargo	Air Express International indicated that a packaged opened during the sort at its Erlanger, KY facility. The package contained 17 lithium ion batteries. As one of the batteries was being returned to the package, it shorted out and caught fire. One employee was injured and treated at the facility.
3/24/2012	DOT 5800.1 Form No E2012040410	Lithium-ion	Battery powered device	Atlas Air Cargo	Cargo	Report from Atlas Air indicated that a package caught fire at its Incheon, Korea facility. The package appeared to contain a lap top computer.
3/2/2012	DOT 5800.1 Form No I2012030493	Lithium-ion	N/A	FedEx	Cargo	Report form Federal Express indicated a fire in a package at its Toluca, Mexico facility. When asked, the consignee reported that he had ordered a lithium battery for a bicycle.
2/25/2012	Air Carrier report	Lithium-ion	Lithium-ion battery powered surf board	FedEx	Cargo	Initial report form Federal Express indicated that a smoking unit load device was discovered at the Memphis, TN airport facility. Inspection revealed the contents of the ULD included a smoking and burning self-propelled surf board.

END