SABATAIR

Deliverable 8: Final Project Report

Dissemination level[1]	CO	**Due delivery date**	
Nature[2]	R	**Actual delivery date**	21/09/2020

Lead beneficiary	**VITO**
Contributing beneficiaries	AIRBUS, ALGOLION, *IMPACT-SOLUTIONS, DGSAFETY GROUP*

Document Version	Date	Author	Comments[3]
V0.0	10.01.2020	Consortium	Creation
V0.1	15.05.2020	VITO on behalf of the Consortium	Submission to EASA for review
V0.2	14.09.2020	Comments from EASA & SC members	
V1.0	18.09.2020	VITO on behalf of the Consortium	Accepted EASA/SC comments and changes. Submission to EASA and EC
V1.1	21.09.2020	VITO on behalf of the Consortium	More details on Phase IV tests added. Final submission to EASA and EC

[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)

[2] Nature of the deliverable: **R** = Report, **P** = Prototype, **D** = Demonstrator, **O** = Other

[3] Creation, modification, final version for evaluation, revised version following evaluation, final

Table of contents

List of Figures

Executive Summary

This report summarises the results obtained during the Sabatair project, which started on November 30th 2017. It presents the main achievements of the project as reported in detail in the other project deliverables.

The main objective of the Sabatair project was to propose and evaluate the existing and novel potential mitigating measures to enhance the safe transportation of both lithium-metal and lithium-ion cells and batteries as cargo on passenger and cargo aeroplanes. The effectiveness of these solutions and measures underwent validation through a series of extensive modelling studies and experimental tests, which were conducted taking into account the relevant environmental and aircraft operating conditions to which the batteries and cells would be exposed.

The experimental tasks performed in the Sabatair project included proposing suitable testing methods for the assessment of the effectiveness of packaging solutions, together with a study of how to prevent the involvement of lithium batteries in an external fire that could originate in a cargo compartment from cargo items other than batteries or cells.

The Sabatair project performed a comprehensive survey in which potential mitigation measures were identified and assessed using a multi-layered approach.

A major accomplishment of the Sabatair project was the creation of safety risk assessment guidance for air transport operators when using the identified solutions and measures in their daily operations.

The project was broken down into several tasks. In Task 1 of the project, potential safety hazards related to lithium cells and batteries and their transport were identified. This task, by contributing to a better understanding of the risks and mitigating measures associated with the air transport of lithium metal and lithium ion batteries, provided an essential input to the creation of the risk assessment guidance (Task 5 of this project).

The purpose of Task 2 was the assessment of the effectiveness of the packaging performance tests as described in the draft SAE AS6413 standard (November 2018 version), which is under development. As the standard is still in draft form, with a number of parameters under review, the results of the Task 2 tests and thermal modelling were regularly communicated to the G-27 Committee to further help refine and develop the draft standard.

A test rig based on the definition given in the November 2018 draft of SAE AS6413 was built and used throughout this task. The detailed description of the test rig and of the test equipment used in the tests conducted in the context of Task 2 can be found in Deliverable D2a.

The testing activities conducted in Task 2 also provided relevant information to generate representative thermal models enabling the simulation of thermal runaway[4] propagation inside lithium cell packages. A cell thermal model was built to:

(i) simulate the thermal runaway initiation mechanism and the associated heat propagation inside the cell;
(ii) model the propagation of a thermal runaway inside a package filled with Li-ion cells, and
(iii) predict the performance of a given packaging scenario.

Thermal modelling of the propagation of thermal runaways in cells with and without mitigating measures was performed considering different values of the State of Charge[5] (SOC). Thermal modelling provided sufficient accuracy to design some mitigation strategies that may contribute to preventing the propagation of thermal runaways. Several simulated cases provided a good qualitative understanding of the effectiveness of the identified mitigating measures.

The testing activities conducted in the context of Task 2 were distributed over four consecutive phases. At the end of each phase, the outcome generated was analysed to determine whether there was any need to adjust and refine the plan and scope of the subsequent phase. Having identified the key variables in Phase I, Phase II (which included a sub phase identified as Phase IIb) was dedicated to the identification of methodologies for improving the control of the rate of heating and the type and position of the heater, and determining which thermocouple location was best for controlling the transfer of heat. Phase III was a follow on from Phase IIb which focused on the effect of differing rates of heating. In order to compare the physical results with those of the thermal modelling (carried out in Task 3), Phase IV then ran tests using the "Reduced Cell Configuration" test layout within UN-certified fibreboard boxes and applying the Phase III initiation test set-up.

Task 3 presents a summary of the proposed mitigating measures to be used in addition to, and in combination with, packaging. An extensive review was carried out and

[4] The definition of a thermal runaway can be found in various standards, such as RTCA DO 227A. We propose to refer to the text used in the draft of SAE AS6413: A thermal runaway results from the initiation of an irreversible exothermic chemical reaction within the cell causing an uncontrollable release of internal electrical and chemical energy, resulting in a rapid and accelerating rise of temperature. The expected consequences of the thermal runaway in a lithium battery are the potential emissions of gas flames and particles.

[5] The State of Charge (SOC) of a cell or battery is the residual electrical capacity remaining in the cell or battery expressed as a percentage of the rated capacity. Rated capacity means the capacity, in ampere-hours or milliampere-hours, of a cell or battery as measured by subjecting it to a load, temperature and voltage cut-off point specified by the manufacturer. The following standards published by the International Electrotechnical Commission (IEC) provide guidance and methodology for determining the rated capacity:

(1) IEC 61960 (First Edition 2003-12): Secondary cells and batteries containing alkaline or other non-acid electrolytes -Secondary lithium cells and batteries for portable applications;
(2) IEC 62133 (First Edition 2002-10): Secondary cells and batteries containing alkaline or other non-acid electrolytes -Safety requirements for portable sealed secondary cells, and for batteries made from them, or use in portable applications;
(3) IEC 62660-1 (First Edition 2011-01): Secondary lithium-ion cells for the propulsion of electric road vehicles-Part1: Performance testing.

a comprehensive summary was prepared describing possible mitigation measures for the whole spectrum from the selection of cargo compartments, packaging, measures in addition to or complementing packaging at the cell and battery level, and regulatory options. Detailed tables were developed reviewing the various mitigation measures in relation to their characteristics, technology readiness levels, cost-effectiveness, probability of usage, practicality, possible interactions and negative impacts with other measures, and the expected level of protection that they could provide. Recommendations were also provided for testing outside the scope of this project in order to increase the relevance of this work as an aid to others beyond the scope of this project.

A new software early warning failure detection method was successfully demonstrated to enable the early identification of the precursors of cell or battery thermal runaway. Based on quantitative algorithms, the software was shown to be more sensitive to the early changes in a cell that lead to a thermal runaway and other types of degradation than conventional evaluation techniques. The causes of thermal runaways that might be prevented and/or detected by this measure are internal short circuits that might be initiated by cell defects induced by manufacturing defects or post-manufacturing abuse or misuse of cells. Due to the need to have access to the data related to the status of the cells, this technique could potentially be used only after the production of the cell and prior to its packaging and shipment. As a consequence, this technique is not proposed as a mitigating measure that could be implemented in the short term in the supply chain.

Full-scale fire tests were conducted in Task 4 to assess the effectiveness of certain mitigation measures identified in Task 3, in particular, the use of a Fire Containment Cover [6](FCC), to prevent the involvement of lithium cells or batteries in a fire event initiated externally to the lithium battery packaging. The tests were performed in a test chamber designed to evaluate the performance of the extinguishing agents used for fire suppression in Class C cargo compartments of large aeroplanes.

The tests performed showed that, for the tested cell configurations and SOC conditions, FCCs, in combination with the built-in fire suppression system of an aircraft, may provide adequate protection against the threats of an external fire event.

The outcomes from Tasks 1 to 4 were taken into account in Task 5 to develop guidance to assist operators in the creation of their own safety risk assessments for the transport of lithium batteries when carried as cargo. When identifying specific hazards, evaluating risks and implementing appropriate safety risk controls in their operations, operators should give consideration to a multi-layered risk mitigation strategy. The safety risk assessment guidance in Task 5 does not focus on or recommend the use of a specific risk assessment model or tool. Whichever model the operator chooses, the capabilities and limitations of the model need to be taken into account, including areas such as ease of use, accessibility and adaptability to different aircraft operations.

[6] ETSO-C203 gives the requirements which fire containment covers (FCC) must meet in order to be identified with the applicable ETSO marking.

Introduction

Lithium rechargeable cells and batteries are the battery systems of choice for over 2 billion consumer electronic devices (laptops, cell-phones, tablets, etc.) produced each year, for various types of electric vehicles, and they are also used in many aerospace, medical and defence applications. Most of the 9 billion cells produced annually need to be transported, many by air, from their points of manufacture to end-users and Original Equipment Manufacturers (OEMs) around the world. Based on an estimate from the International Air Transport Association (IATA), approximately 1.2 billion lithium-ion and lithium-metal cells and batteries were transported by air in 2008. This number increases annually, with a reported estimate of 6 billion lithium cells and batteries transported by air in 2015. Multiple incidents, due to fires and thermal events caused by lithium batteries, have been observed in air cargo in recent years.

In 2016, the Council of the International Civil Aviation Organization (ICAO) prohibited the transport of lithium batteries shipped alone (without equipment) as cargo on passenger aircraft. The ICAO Council's decision has been effective since 1 April 2016, and only applies to lithium-ion batteries shipped as cargo on passenger aircraft, and not to those contained in personal electronic devices carried by passengers or crew or when transported on cargo aircraft. This prohibition was the result of extensive reviews undertaken by the ICAO Air Navigation Commission, and ICAO's Dangerous Goods, Flight Operations, and Airworthiness panels. Due to concerns related to lithium batteries and aircraft fire suppression capabilities in the event of a fire, it was determined that the transportation on passenger aircraft of lithium-metal and lithium-ion cells or batteries as cargo when shipped alone (according to UN 3090 and UN 3480) should be forbidden as a temporary measure until controls are put in place to establish an acceptable level of safety. ICAO requested the SAE International Standards organization to create a standardization committee (SAE G-27 Committee) to develop a performance-based packaging standard as one of these controls. The aim of this standard is to contain a lithium battery event within a package as part of a multi-layered mitigation strategy.

SAE International has launched the 'G-27 Lithium Battery Packaging Performance Committee' to develop the SAE standard reference number AS6413 (Performance based packaging standard for lithium batteries as cargo on aircraft). The SAE G-27 Committee is comprised of representatives from ICAO, the International Air Transport Association (IATA), the International Federation of Airline Pilots Association (IFALPA), the International Coordination Council for Aerospace Industry Association (ICCAIA), the European Association for Advanced Rechargeable Batteries (RECHARGE), the Rechargeable Battery Association (PRBA), the Battery Association of Japan (BAJ), defence agencies, aircraft operators/airlines, packaging manufacturers and regulatory authorities, including the European Union Aviation Safety Agency (EASA) [1].

Addendum No. 4 to the 2015-2016 Edition of the ICAO Technical Instructions[7] for the Safe Transport of Dangerous Goods by Air prohibited the transport of lithium-ion batteries as cargo on passenger aircraft. Lithium-metal cells and batteries were already forbidden to be transported on passenger aircraft. The ICAO prohibition was intended to be a temporary measure until controls are put in place which establish an acceptable level of safety. The controls include:

1) The development of a performance-based packaging standard to contain any internal packaging thermal event within a package (SAE AS6413);
2) The creation of guidance and supporting material for air operators to be used for safety risk assessments to evaluate the risks associated with the transport of lithium batteries on aircraft;
3) The development of additional operational controls to mitigate the aviation-specific risks posed by the transport of lithium batteries, including means to identify and communicate the specific hazards associated with different cell or battery types, and to ensure the transparency of shipments, including those not subject to full regulation; and
4) The introduction of measures to reduce levels of non-compliance.

The Sabatair Project is a research project funded by the European Union, coordinated by VITO and supervised by EASA and DG MOVE with the support of a Scientific Committee. The scope of the Sabatair Project, as defined in the Tender (N° MOVE/C2/2016-353), was to study potential mitigating measures that can be used to enhance safety when transporting lithium-metal and lithium-ion batteries (as cells and batteries shipped alone according to UN 3090 and UN 3480, and not devices containing such cells or batteries) as cargo on passenger and cargo aeroplanes. Potential safety risks were identified, the effectiveness of various measures was assessed, and risk assessment guidance was developed to enable operators to establish and evaluate safe conditions for air transport.

[7] International Civil Aviation Organization (ICAO) Document 9284, 'Technical Instructions for the Safe Transport of Dangerous Goods by Air'

Task 1: Definition of the baseline for the project: review of the state of the art and hazard identification.

I.1 Overview of the objectives

The objective of this task is to assess the safety hazards posed by the air transport of lithium cells and batteries. This work contributes to identifying and understanding the risks, including their causes and consequences, so that mitigations can be developed and put in place. The results of this first task represent the baseline for the following tasks (Tasks 2 to 5).

I.2 Main results

A thorough review of the scientific literature regarding lithium battery hazards and their possible causes and consequences was performed, and the outcome of this work is reported in Deliverable D1[8]. The report served as a baseline document for this project in understanding the basics of energetic failures in lithium batteries, state-of-the-art methods for testing, and the importance of lithium battery safety in air transport.

The typical working principle of a lithium battery was explained with a schematic, and the practical design variants in terms of construction methodology and form were described. The logistic life cycle of a cell or battery was characterised by means of a flowchart, demonstrating the importance of the implementation of safety measures during their transportation.

Different failure modes and the hazards associated with each were described. Energetic failures or thermal runaways in lithium batteries were investigated in detail.

Cell or battery failures can be considered from a thermal point of view, and can then be divided into two categories: energetic and non-energetic failures. This division depends upon whether the origin of the fault can cause sufficient heat in the cell to lead to a self-sustaining exothermic reaction within the cell. Actually, the temperature of a cell is determined by the heat balance between the amount of heat generated and the amount dissipated. When a cell is heated above a certain temperature (usually above 130-150°C), exothermic chemical reactions between the electrodes and electrolyte set in, raising its internal temperature. Test evidence shows that if the heat generated is dissipated effectively, the temperature of the cell will not rise abnormally. However, if the heat generated is more than the heat that can be dissipated, the temperature of the cell will continue to rise, and will further accelerate the chemical reactions, causing even more heat production, eventually resulting in a thermal runaway.

The severity of a thermal runaway event depends on many factors, but it is mainly related to the amount of energy that the cell contains, i.e. the state of charge. It is also affected by the type of chemistry of the cell, however, all kinds of lithium battery chemistries may undergo thermal runaway under certain conditions. It is important to note that the conditions that may lead to thermal runaway can develop at different rates to reach the event threshold over a range of timeframes from minutes and hours to even

[8] *D1: Review of the state-of- the-art for lithium battery fire – explosion – smoke risks and associated mitigating measures; D1b: Hazard Identification and Characterisation (Submitted 15/03/2018)*

days, depending on the specific design and construction of the cell or battery, the type of failure, and the operating environment.

The causes of such energetic failures, such as poor cell design, defects during the manufacturing process, thermal abuse, and mechanical and electrical abuse, are described. Emphasis in this project was given to thermal, mechanical and electrical causes, since they are the most relevant to cargo transportation conditions. A range of topics, including the consequences of improper cell placements in case of damage, overcharge/over-discharge and improper thermal isolation between cells are discussed.

The factors influencing thermal runaways were studied. These influencing factors directly affect the intensity of a thermal runaway reaction. Firstly, the state of charge is an important factor; it is shown that a lower SOC causes less of a hazard since there is less electrical energy to be released in a thermal runaway event. Secondly, the chemistry of the cell affects the intensity of the thermal runaway event, since there are variations in the flammability of the cell components. Thirdly, the needs for proper ventilation and active methods to dissipate the heat out of the cell or battery and its immediate surroundings are highlighted, thus ensuring safe storage/operation at a nominal temperature.

The safety mechanisms available to avoid such hazards and/or prevent thermal events are subsequently reviewed. These include conventional safety devices such as safety vents, thermal fuses and other circuit breakers, self-resetting devices, shutdown separators, and use of non-flammable or fire-resistant materials for the construction of the cell or battery.

A list of the relevant air transport occurrences involving lithium cells/batteries transported as bulk entities, together with some details of their likely causes, was provided. The list gives an insight into the frequency of lithium battery specific occurrences in the air transport segment. Although the list is not exhaustive, it provides an overview of the most likely causes of battery-fire events. From the review, it can be inferred that the most common causes for battery fire events are external short circuits due to unprotected terminals or improper packaging. The need for compliance with the existing ICAO dangerous goods transport requirements and UN testing requirements is emphasized by the review.

A summary is provided of the investigation report into one of the major air accidents [N571UP] which occurred due to a fire that is likely to have originated in a cargo compartment containing lithium batteries. The summary includes the discussion of the causes (lithium batteries, inadequate fire detection), the evaluation of the main contributing factors (ineffective fire suppression methods for fires that develop in class E cargo compartments, the inadequacy of regulatory standards at the time for passive fire suppression, and the inadequate implementation of dangerous goods packing regulations for lithium batteries), as well as the safety recommendations (to standardise packaging, to conduct further tests on lithium batteries in flight cargo, and to review the existing packaging standards from ICAO).

Furthermore, summaries of the reports from two test centres on the flammability and packaging of lithium batteries were provided. The tests were performed under different scenarios such as individual cells, multiple cells with packaging, and fire suppression with

Halon. Based on the evidence generated by the tests, it was concluded that a fire event involving a relatively small number of lithium-ion 18650 cells may create a level of concentration of vented gases that could easily generate an explosion when such gases are exposed to an external ignition source. While Halon 1301 was reported to be effective in suppressing an electrolyte fire, extinguishing the fire, and preventing any additional fire from subsequent venting, the ignition of the gases released by the cells may result in a pressure increase in the cargo compartment that could cause the activation of decompression features, leading Halon to leak, and thus making fire suppression ineffective.

Task 2: Assessment of the effectiveness of the packaging performance tests

I.3 Overview of the objectives

The objectives of Task 2, as initially defined in the tender, were to identify packaging solutions for the transport of lithium cells and batteries by air, to assess their effectiveness by a set of tests to be developed, and then generate a proposal for a standard. After the start of this project, the scope was altered as a draft of SAE AS6413, which was already in development.

The objective of SAE AS6413, 'Performance based package standard for lithium batteries as cargo on aircraft', is to develop performance-based packaging tests as a basis for a packaging standard to transport lithium batteries as cargo. The standard provides specified test methods and criteria to assess packages that could be used to handle and contain hazards that are observed during thermal runaways of lithium batteries. It is intended that controlling the consequences of a cell or battery failure within a package should prevent uncontrolled fires and pressure pulses that may compromise the effectiveness of the fire suppression systems installed in Class C cargo compartments. The main thermal runaway hazards that are being addressed are flames, fragments, flammable vapours, and high surface temperatures. Potential hazards from vapours or smoke that could affect the health of passengers are not addressed in the standard.

At the time of writing this report, the SAE AS6413 standard remains under development, and the current discussions within the SAE G-27 committee may potentially lead to further changes in the draft standard. There is general agreement between the SAE G-27 committee members on which kinds of test methods should be included in the standard, but several technical aspects are still being modified during each iteration of the SAE AS6413 document.

The focus of Task 2 was then shifted from assessing packaging solutions to the assessment of the effectiveness of the tests as described in the draft version of AS6413. Based both on the discussions during the SAE G-27 meetings and on the feedback obtained from EASA and the Scientific Committee members supervising this project, it appears that more experimental data is needed to validate the test procedures that are currently in the draft standard. This was confirmed by the experimental results obtained from performing the first set of tests. The test results from two commercially available Li-ion cell shapes showed non-repeatable results. As a result, the focus of this task was then directed to the evaluation of the test procedure parameters.

The testing activities conducted in the context of Task 2 were distributed over four consecutive phases. At the end of each phase, the outcome generated was analysed to determine whether there was any need to adjust and refine the plan and the scope of the subsequent phase.

The November 2018 draft of the SAE AS6413 standard was used throughout this task. Changes and updates to the base standard set-up made during later amendments to the draft standard were taken into account.

All the tests performed in this task are based on Test VIII from the SAE AS6413

“Reduced Cell Configuration” test. This test was selected because it requires a small number of cells, which makes it easier to evaluate the different test set-up parameters, as it generates less exothermic energy during a cell thermal runaway. This test consists of placing an ‘initiation source’, covered with thermal insulation material, in contact with an ‘initiation cell/battery’ that is covered with heat insulating material. A thermocouple should be placed at the location most representative of the internal temperature of the cells/batteries, which is defined for cells under 50 grams to be on the opposite side of the cell from where the ‘initiation source’ has been placed. The temperature of the thermocouple placed on the opposite side of the ‘initiation source’ must be monitored, and should rise by 5°C to 20°C per minute until the ‘initiation cell/battery’ reaches a thermal runaway or a temperature of 200°C. If the ‘initiation cell/battery’ has reached a thermal runaway prior to reaching 200°C, the power of the ‘initiation source’ must be removed. If no thermal runaway is observed, and after reaching 200°C on the thermocouple reading, the temperature should be maintained above 195°C. This should be performed for 1 hour or until a thermal runaway takes place. The test procedure should be ended 5 hours after the removal of power from the ‘initiation source’, unless the package shows a failure before that.

I.4 Main results

I.4.1 Construction of the test chamber

A test chamber was designed and constructed in accordance with the requirements of the draft SAE AS6413 standard as of November 2018. The chamber was designed in such a way that changes could be easily implemented given that the draft standard remains in development.

The test rig consists of an airtight chamber with a movable bottom tray that allows the volume of the chamber to be adjusted depending on the size of the test article so that a free air space of 0.3 m^3 is maintained. The sides of the chamber are made of transparent fire-retardant acrylic Perspex, and the top and bottom are constructed out of carbon steel. Perspex allows for easy viewing, and it is also readily available and replaceable. This was considered to be important, given the unknown parameters of the testing, as well as the unknown severity of the thermal runaways likely to be observed.The top of the chamber has a square cut-out to allow for the installation of a pressure relief system. The completed test chamber is shown in Figure 1.

Figure 1: Test chamber constructed to the specifications shown in the AS6413 draft standard.

A number of preliminary tests were carried out during June and July 2018. The purposes of these tests were to verify the performance of the constructed apparatus and to ensure that the apparatus was performing as designed. The testing was also used to refine the laboratory procedures, and for the risk, health and safety assessments required to carry out a future test program. This testing period also allowed individual components to be verified and calibrated in line with the ISO 17025 procedures, where applicable, and, where not, to ensure that the apparatus was in line with the reference SAE AS6413 draft.

A detailed description of the test rig and the test equipment used in the tests conducted for Task 2 can be found in Deliverable D2a[9].

I.4.2 Lithium-ion cell selection for testing

The cells selected for use in the tests of Task 2 were chosen after a thorough review of the literature on the behaviour of each thermal runaway of a lithium-ion chemistry cell, and market research. As the worst thermal runaway in terms of the maximum temperature was identified to be relevant for the testing of Task 2, our research was focused on searching through scientific journals to find the average maximum temperature level of the thermal runaway that each cell chemistry could potentially provide.

Based on the results found in the literature, it was decided to concentrate on the $LiNiMnCoO_2$ (NMC) and $LiNiCoAlO_2$(NCA) chemistries, as these were found to have the most severe thermal runaway behaviour. After an extensive market survey, it was decided to work with NMC-based cells, as they were commercially available in various shapes and capacities.

Following the identification of the cell chemistry to be used, two types of cells were purchased to investigate the effects of the cell form factor. The different types of cells played a role in terms of evaluating thermal runaways, and also their placement inside a package that was set up according to the SAE AS6413 draft standard. Two NMC cells with the same capacity (3.2 Ah) were chosen with a different cell type (cylindrical and soft prismatic). This allowed comparisons to be made between the two cell types based on a similar energy content of the cells. The cells were purchased from a trusted cell supplier

[9] *D2a: Identification of packaging solutions and assessment of their effectiveness (Submitted 08/05/2020)*

used for other European projects. The cells are certified to comply with the UN 38.3[10] Tests.

I.4.3 Sabatair test program

As mentioned earlier, the test programme can be divided into four consecutive phases. The following is a summary of the results obtained during these test phases. Further details can be found in Deliverable D2b[11], where detailed test reports have been collated.

In Phase I, the objective was to conduct trial tests in accordance with the proposed SAE AS6413 draft standard (November 2018 version). The key activity of Phase I was to evaluate the repeatability of the 'Reduced Cell Configuration' test with pouch cells, cylindrical cells, and using two different SOC levels (30% and 100%) (see the schematics of the Phase I test set-up in Figure 2). The Phase I test was not designed to evaluate the performance of the package in the event of a cell thermal runaway.

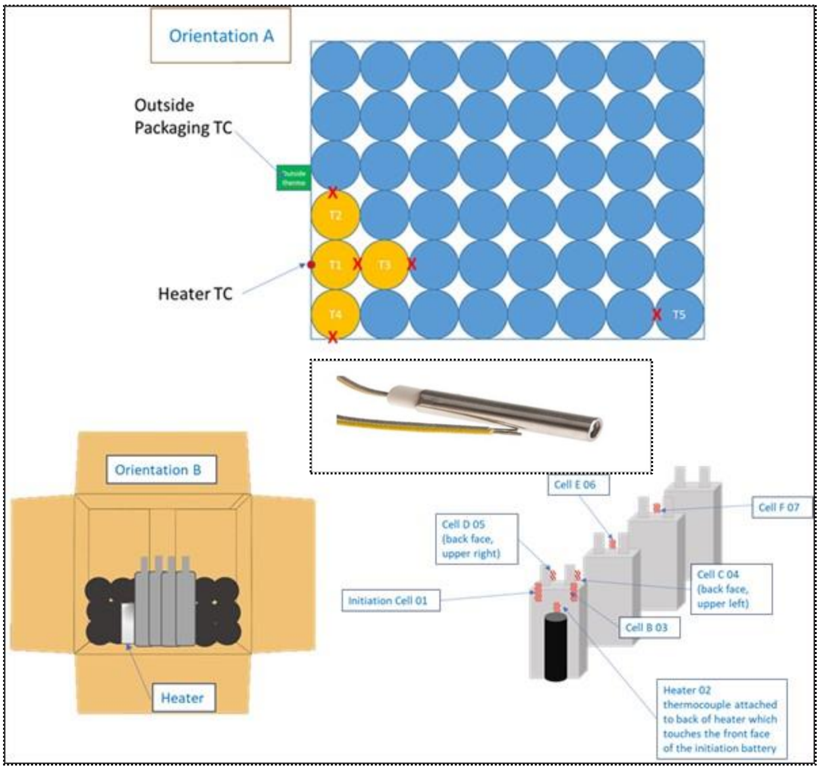

Figure 2: Test set-up in Phase I (orientation A & orientation B) including a picture of the heater cartridge.

The Phase I testing highlighted that the test set-up and procedure proposed in the SAE AS6413 draft standard could lead to a lack of repeatability of the test results obtained. The key variables to improve repeatability were identified to be the position of the heater, the type of the heater, and the method of control of the heater. As a result, the Phase II testing that followed focused on defining and controlling these variables in order to allow for meaningful further testing.

The purposes of the tests of Phase II were to:

[10] UN (United Nations) Manual of Tests and Criteria

[11] *D2b: Assessment of the effectiveness of the packaging performance tests (Submitted 08/05/2020)*

- define the type of heater and the position of a heater for both the 18650 and pouch cells (type, shape, power rating etc.);
- determine the optimal method of controlling the heater to obtain a linear temperature ramp increase;
- define how to prevent thermal energy from being transferred to the surrounding items (other cells, packaging) other than the initiation cell, for example by using suitable insulation methods; and
- define how to ensure that the optimal amount of thermal energy was transferred to the initiation cells to cause a thermal runaway.

The Phase II tests followed multiple test set-ups (see Figure 3-5). This was to attempt to keep a consistent rate of increase in the temperature of the initiation cell, given the variability in the way the heat was transferred from the heater to the initiation cell. The different orientations allowed further key parameters to be identified, and optimization to increase the repeatability of the tests. During this phase of testing, different sets of temperatures were selected, depending on the type of heater used.

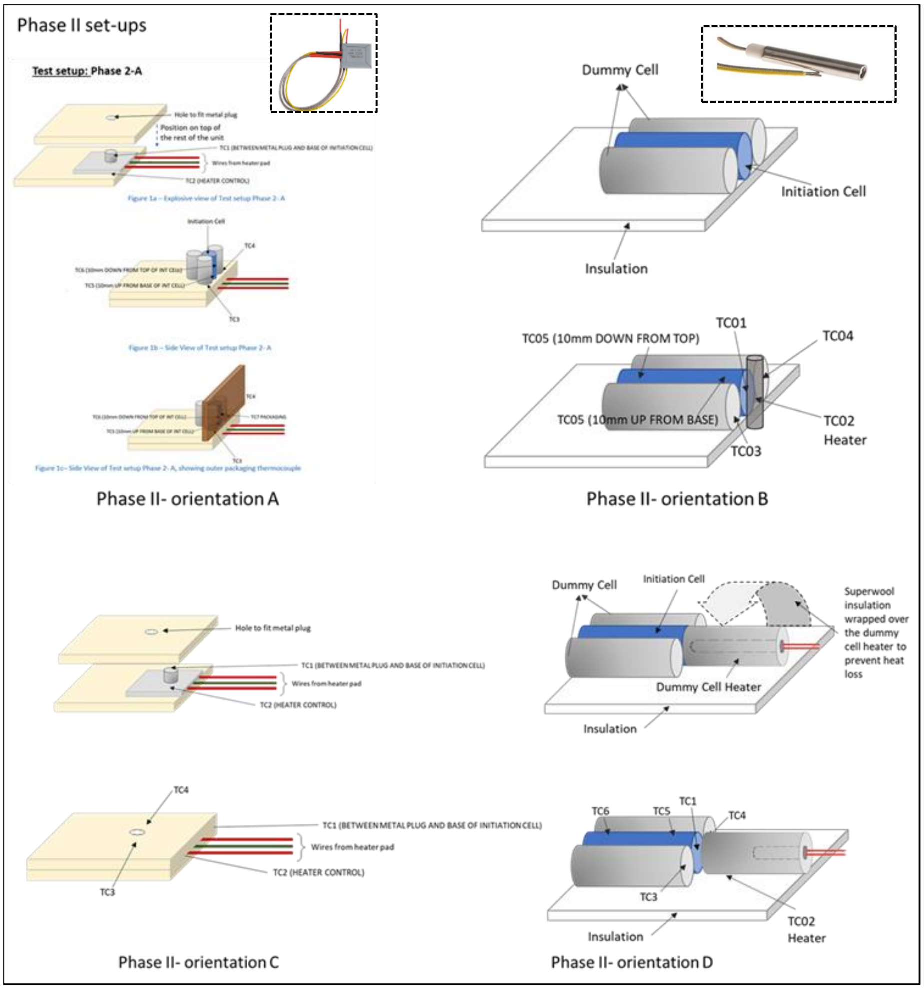

Figure 3: Test set-up in Phase II including pictures of the two types of heaters.

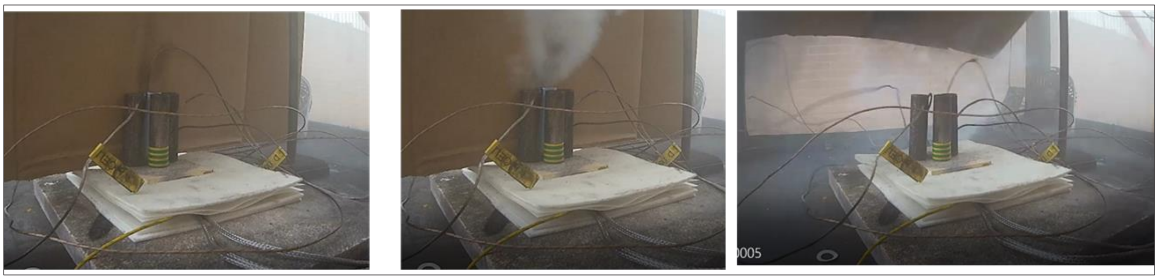

Figure 4: Pictures of Phase II (Test 10) (left) Beginning of the Test; (right) Beginning of Thermal Runaway; (centre) Experienced Thermal Runaway.

Figure 5: Pictures from the Phase II (Test 16) (left) set-up; (right) during testing showing the heater cartridge becoming detached from the initiation cell.

The results of these Phase II tests identified the rate of the external heating as a key parameter in being able to repeatedly induce a thermal runaway, with even small differences in heating rates causing different test results. Furthermore, it was concluded in Phase II that the heater should distribute heat in a confined space (pin point), rather than spreading heat evenly over the cell. This conclusion was reached by observing the following:

- The temperature increase recorded in the area of contact between a conventional heater and the initiation cell was not as consistent and linear as required.
- An observation was made that the heater cartridge and the cylindrical cell were not always in good contact. This means that the heater may not have the expected level of contact with the initiation cell in each test run.

Therefore, one of the novel ideas developed in Phase IIb was the design of a heater that more closely approximated the effect of heating generated by an internal defect in the cell. In fact, the heating effect of an internal short circuit in a cell is localized. Thus a heating element that ensured a point contact with the cell was developed and proposed to be used, rather than a heating element that would distribute heat over a large cell area. This design of a point contact heater having a contact area of 64 mm^2 is shown in Figure 6-8.

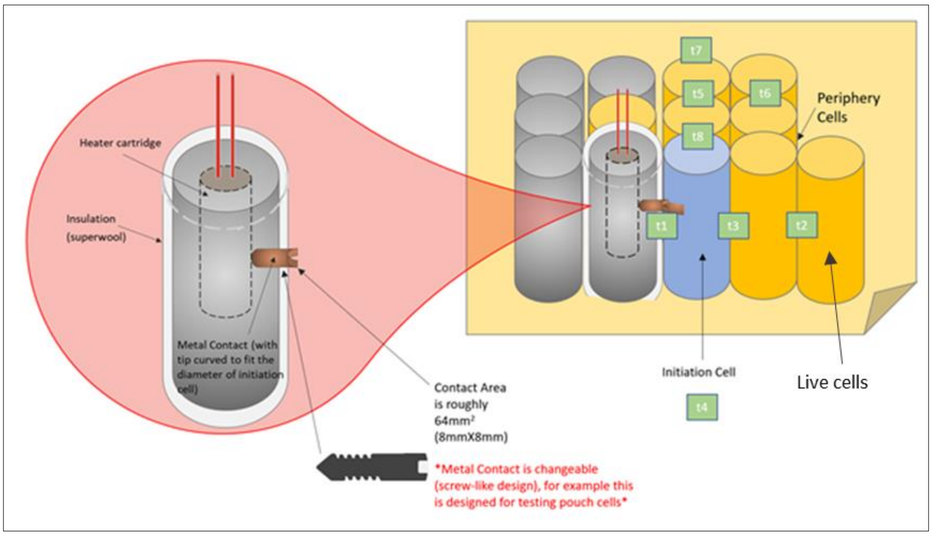

Figure 6: Schematic of the Phase IIb test set-up with the adapted heater contact.

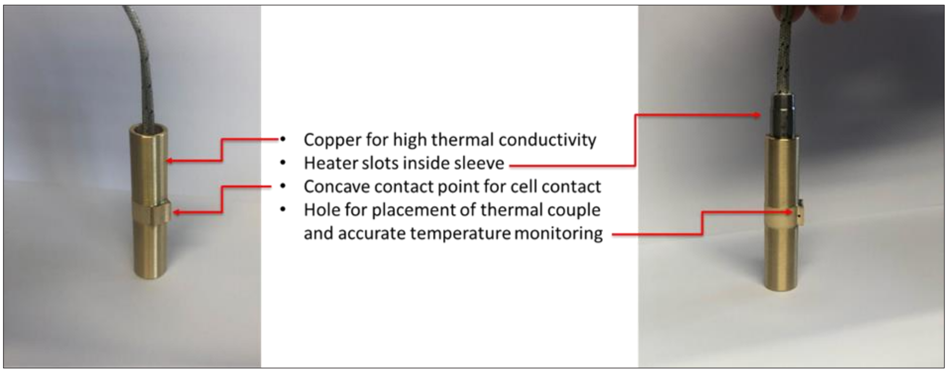

Figure 7: The custom designed thermal conductive heater.

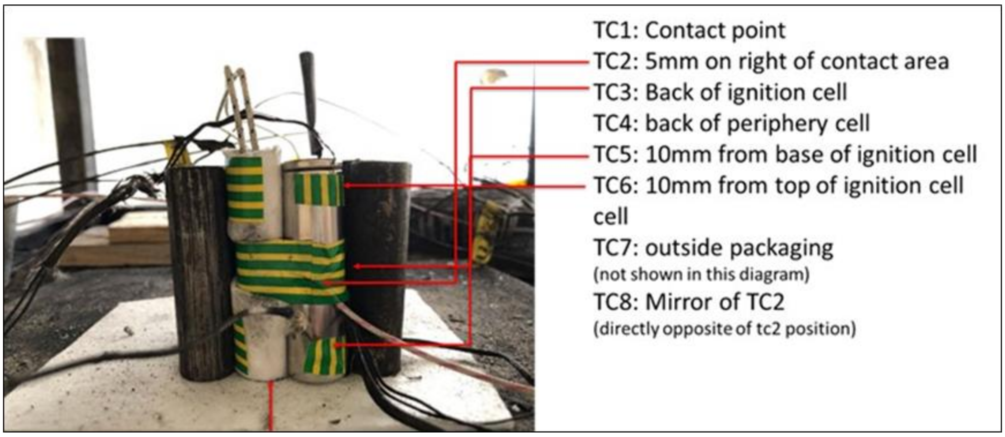

Figure 8: Phase IIb set-up

Phase IIb focused on investigating the consistency of thermal runaway events by applying heat to the surface of a cell and monitoring the temperature of different locations on the external surface of the cell. This allows for the determination of the optimal rate of temperature rise that is critical to the test. Furthermore, the data obtained would indicate the most suitable position for the placement of the control thermocouple.

It should be highlighted that the problems mentioned in this section are related to the method of testing, and not to the specifications of the standard. The purpose of Phase IIb was to provide greater clarity to test houses to ensure the consistency and repeatability of test results.

Phase IIb demonstrates how, thanks to the improved test set-up, good repeatability and consistency of the thermal runaway events was achieved. The bespoke heater unit design (including a thermal conductor & heater cartridge, see Figure 7) can fit into a typical package layout. A rate of temperature increase of between 5°C and 20°C/min was achieved, although only as an average rate throughout the duration of the test.

Phase IIb showed that the proposed test set-up is appropriate, and that repeatability is achievable. Nevertheless, the ramp rate is not as linear as expected, therefore the heater temperature should be more controlled, as the next phase of the task demonstrated.

Phase III repeated the test set-up from Phase IIb (illustrated in Figure 8). The objective of this phase was to achieve a more linear temperature ramp rate with the heater. This phase was intended to understand the effects that the linear heating rate and the positions of the thermocouples may have on the severity of the thermal runaway event. Moreover, the repeatability of the test set-up continued to be a key focus in this phase.

In the tests conducted in Phase III, the cells surrounding the initiation cell were active cells (*i.e.* not dummy cells), and the set-up included the use of outer packaging. As Phase III progressed, a variation in the set-up was introduced because the data obtained from the initial test runs indicated opportunities for improvements. The improvements mainly consisted of the definition of a thermocouple position that could lead to obtain more accurate results. These changes improved the rate of temperature rise in the initiation cell (TC3 in Figure 8), which also better aligned with the input used for the thermal modelling.

The objective of the thermal modelling was to complement the experimental tests, and also to replace them when necessary. Through the thermal modelling carried during this project, it was possible to provide additional reasoning and rationalization regarding the set-up of the experimental procedure as described in the SAE AS6413 draft standard, and to provide guidance in the selection of mitigation measures for further experimental investigation.

I.4.3.1 The thermal model

To help with these challenges, a thermal model was developed. This thermal model simulates heat propagation over an array of lithium-ion cells within a package to obtain better insight into the transient heat flow across the package. In the numerical model, the energy equation was solved using the Finite Volume Method (FVM) based solver to simulate heat transfer by conduction and radiation. Inside the transportation package, heat transfer by air convection and the presence of flue gases was discounted. Instead of modelling detailed electrochemical mechanisms leading to the heat generation in the cell, the heat generation inside the cells was directly imposed by an experimental heat generation profile. The computational domain can be set depending on the case of interest, with appropriate material properties and boundary conditions. The model can be used to simulate the behaviour of a single cell (pouch or cylindrical), as well as of a group of cells in a package. In the study, the model was first validated with experimental results, and then used to simulate different test scenarios relevant to the project goals.

1.1.1.1 Validation of the thermal model

The validation of the thermal model was achieved with experimental data obtained from the different experimental tests performed during this project. This was done using two kinds of experimental set-up, the first one with a single cell heated with a point heater source and insulated on all sides, and the second one with measurements carried out on a group of cells placed together, with one cell heated with a point source. Appropriate material properties and boundary conditions were applied for the different cases, and the temperature evolution at different points on the cell was compared with temperature evolution data obtained from experiments. Within the limitations of experimental measurement data and numerical results, the thermal model can be considered as validated and can be used to provide a qualitative assessment of various mitigation strategies for the prevention of thermal runaways.

I.4.3.2 Assessment of the thermal runaway initiation parameters through cell thermal modelling

The thermal model can be used to estimate the internal temperatures of a cell both before and during the initiation of a thermal runaway. This is very beneficial in understanding how heat is conducted within a cell before estimating the propagation of a thermal runaway between multiple cells in a package. Simulations were performed to simulate the heating of a cell on one side, and to observe the temperature increases at different locations on the cell for different heater sizes and heating rates. It was observed that the heat propagates according to directional thermal conductivity, thus lower temperature values were measured in the point of the cell opposite to the heater location. Higher heating rates led to faster heating and higher maximum internal temperatures. The larger the surface area of the heater, the faster the heating, and the higher the average internal temperature of the cell.

I.4.3.3 Modelling the propagation of a thermal runaway

The different factors affecting the initiation of a thermal runaway and its propagation which were taken into account in the thermal modelling were the:

- position of the initiation cell (corner, edge or centre of the package),
- stacking of cells,
- SOC of the cells (30% and 100%),
- chemistry of the cells,
- geometry of the cells (cylindrical or pouch),
- packaging material (fibreboard), and
- the geometry and material of the packaging dividers.

Although thermal modelling showed that a thermal runaway initiated with a cylindrical cell placed in the corner of a package was more severe (*i.e.* higher heat generation), the cell position was fixed to be at the centre of the edge of the package as described in the SAE draft standard.

Once the different factors were taken into account, a thermal runaway was induced in the initiation cell, and its propagation inside the package full of lithium-ion cells was simulated. The simulation of the propagation of a thermal runaway was first carried out based on data found in the literature (*e.g.* thermal measurements on a single cell) which did not lead to consistent results, as here, the thermal runaway occurred in a package full of cells, and not in an isolated cell. Experimental data obtained from the Task 2 tests were used for modelling. As explained earlier in Section I.4.3, the SAE AS6413 standard is still in a draft version, and some of the test parameters are still to be defined and confirmed. Further details about the thermal model can be found in Deliverable D2a, and additional thermal modelling results are included in Deliverable D3b.

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

I.5 Overview of the objectives

The goal of Task 3 was to propose additional measures that can be used in addition to packaging as part of a multi-layered approach for mitigating the safety hazards of lithium rechargeable cells and batteries transported as cargo on large aeroplanes. As a first step towards achieving this objective, Task 3 identified mitigating measures in addition to packaging. A test plan was formulated in Deliverable D3a for assessing several of these measures and identifying in coordination with the Scientific Committee and EASA the ones that had higher priorities and were feasible to test within the scope of the Sabatair project. The test plan lists the possible mitigation measures identified by Sabatair, and provides information on, among other items, their target levels. An extract of the test plan is shown in Table 1 below.

Target Level	Mitigation Measure	Test Priority (see Glossary)	Overall Priority (see Glossary)	Cause of Thermal Runaway that is Mitigated (see Glossary)	Consequence of Thermal Runaway that is Mitigated (see Glossary)	Impact Type	Readiness (see Glossary)	Affects Who	Commercial Availability
Cell / Battery	Pre-evaluation of battery state of safety with early warning diagnostic software	HIGH	**HIGH**	Internal defect induced by manufacturing or post-manfufacturing	All Thermal Runaway hazards	Mitigates causes of thermal runaway prior to packaging and loading.	Now	Battery OEM + all shippers	ALGOLiON, www.algolion.com
Packaging	Level - New packaging material and/or new material for the dividers between the cells inside the packaging should have improved flammability performance, e.g., flame retardant materials, intumescent materials, thermal insulation material (Pyrobubble granules, Extover porous foam glass, silica aero-gels, mineral wool, phase change materials, graphite sheets).	HIGH	**HIGH**	Exposure to external fire, heating	Hazardous flames; heating of neighboring cells. Packaging content involvement in an external fire) and/or propogation of battery/cell fire within the packaging and to other packaging.	Mitigation of propagation of external fire	Now	Battery OEMs + all shippers	Plastic containers using flame retardant ABS materials (for example, Husqvarna, UK, http://www.hammondmfg.com/dwg2a.htm , https://www.stephen-webster.co.uk/products/abs-plastic-sheet/fire-retardant/
Operator Equipment	Over-layer fire containment cover applied by Operator	HIGH	**HIGH**	Exposure to external fire, heating, flames, fragments	Hazardous flames; fragments; heating of neighboring ULDs. Pacakging content involvement in an external fire.	Mitigtation of exposure to external fire/heating	Now	Airline (Operator) only	AM Safebridport, https://amsafebridport.com/ ,https://brimstonefireprotection.com/products/heavy-duty-battery-explosion-fire-containment-bag-large-laptop-preventer-hd-edition-20-000-mah , Goodwin Group, https://www.newtex.com/nes/fire-containment-covers , https://www.dupreminerals.com/ , https://flamefortress.com/?currency=USD&gclid=EAIaIQobChMIuJ2dy5nh3gIVz-R3Ch0NrwpcEAAYASAAEgICOPD_BwE , https://www.newtex.com/nes/fire-containment-bags , https://brimstonefireprotection.com/products/battery-explosion-fire-containment-bag-large-laptop , https://www.aviationpros.com/product/11221634/fire-containment-bag , https://www.firechampion.com/products/lbck-small
Alarms	Cargo compartment HF Sensor (inorganic) aircraft equipment	LOW	**LOW**	Exposure to external conductive or corrosive media	Hazardous accumulation of HF inside cargo compartment; also mitigates damage to ULDs and aircraft from hazardous vapors / over-pressure. Catastrophic consequences of a battery/cell fire.	Detection of consequence of thermal ruanway	Now	Airlines	http://www.mil-ram.com/gas-detectors/hydrogen-fluoride-detector.html?gclid=EAIaIQobChMI8qvFnZ7i3gIVy53tCh1LIAjsEAAYAiAAEgKR8PD_BwE , https://www.internationalgasdetectors.com/gases/hydrogen-fluoride/ , https://gasdetection.3m.com/en/gases/hf , http://www.mil-ram.com/gas-detectors/hydrogen-fluoride-detector.html

Table 1: An extract from the 'Additional Mitigating Measures Summary Table' showing the different target levels.

It is realised that not all mitigation measures are relevant for all airlines, cargo operators, shippers and battery/cell manufacturers. Some of the measures were selected to be within the scope of the Sabatair project and were ranked according to their priorities for testing. The project task in which their evaluation would be performed was also determined.

Task 3 included a categorization and critical review of the available hazard mitigation measures besides packaging, and an assessment of their efficiency and cost-effectiveness. Although the survey of possible mitigating measures was comprehensive, it was not exhaustive. Thus, other mitigation measures may exist which were not identified by the Sabatair project.

I.6 Main results

A market screening and review of existing commercially available solutions and of potential solutions that are currently not commercially available was performed to identify a multi-layered approach to the mitigation of safety hazards, and was documented in Deliverable D3a. An Excel file accompanying this deliverable was generated, which identified preventive measures for the causes, and the mitigating measures for the consequences of a thermal runaway.

The different mitigating measures were separated into those that can be applied to:

- the design and manufacturing of cells/batteries,
- the packaging,
- operator equipment, and
- and the designs of cargo compartments.

The readiness level for each mitigation measure and its cost effectiveness were also assessed. In the same manner, the assessment of the potentiality of the measure to be successfully applied was indicated by a low, medium or high score. Recommendations were also provided for testing outside the scope of this project in order to increase the relevance of the work as an aid to others outside this project.

In this Task, a review of the classification of the cargo compartments installed on large aeroplanes was performed, together with a description of the fire protection systems required for each class of cargo compartment. The classification defines the appropriate requirements in terms of fire protection depending on the usage and the location of the cargo compartment. However, only the design of the Class C cargo compartment type was considered relevant to the testing conducted in this project. The outcome of the review is reported in Deliverable D3a. The study conducted in Task 3 supported the selection of the potential mitigating measures to be tested in the cargo compartment mock-up tests conducted in the context of Task 4.

I.6.1 Evaluation of battery safety with early warning diagnostic software

Predicting in advance a likely thermal event in a cell or battery being transported by air may be a useful contribution to improving safety. The move towards prognostics/predictive diagnostics is recognized by the SAE Industry Technology Consortia (ITC) via Recommended Practice JA 6268[12]. The objective of prognostics is to shift from detecting an actual hazard and then taking mitigating measures to minimize its consequences, to preventing it in the first place.

In addition to temperature measurements, smart diagnostic algorithms may be used to examine electrochemical developments that are precursors to a thermal runaway.

[12] https://www.sae.org/news/2019/05/sae-ja-6268-evolution-to-vehicle-prognostics

Internal shorts are characterized by intense local heating. A new method for simulating internal shorts was developed and evaluated that reproducibly drove each cell into a thermal runaway by heating the cell surface at a point contact with an external heater (see Figure 9). Point heating closely simulated the location and area of heat generation due to internal shorts. The heat can be generated by a variety of spot defects such as dendrite formation, defective or torn separators, misaligned electrodes, tab burrs, cell contamination, tab weld splatter, and other items. This new technique was validated on cells of various cell brands, form factors and capacities. It was discovered from these tests that important factors for applying this method include the geometry of the heating element, i.e., the quality of its contact with the test cell, the magnitude of the contact heating area, the rate of heating, the position of the heating point on the cell surface, and the effect of the state of charge of the cell. Thermal runaways were initiated only for cells with 100% SOC. 30% SOC cells did not undergo thermal runaways under the same experimental conditions as those used for the 100% SOC cells. Thus, these particular tests showed that minimizing the SOC reduced the risk of a thermal runaway. However, one general conclusion was that there is no 'one size – fits all' protocol for reproducible, repeatable thermal runaway results.

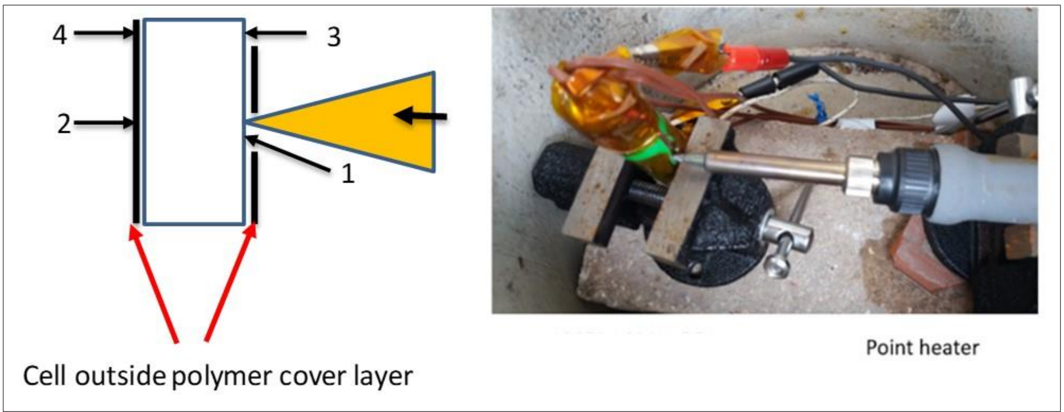

Figure 9: New test set-up to induce a thermal runaway by local heating

An early warning prognostic software program for lithium batteries was developed to provide safety alerts well before a hazard event occurs so that measures can be taken to prevent a fire. This prognostic software was used in the Task 2 and Task 3 testing by applying it to cells during the heating leading up to a thermal runway (see Figure 10 and Figure 11). The causes of thermal runaways that might be prevented and/or detected with the warning prognostic software are internal short circuits that might be initiated by cell defects induced by manufacturing defects or post-manufacturing abuse or misuse of cells. Considering the need to have direct access to the cell to be monitored, this technique can be used only after the production of the cell and prior to its packaging and shipment. The cell manufacturer may supply the shipper with a certificate regarding the state of safety of the cells for transport.

Figure 10: The purpose-built algorithm Demo Box instrument (right side) and software program (on the screen of the laptop).

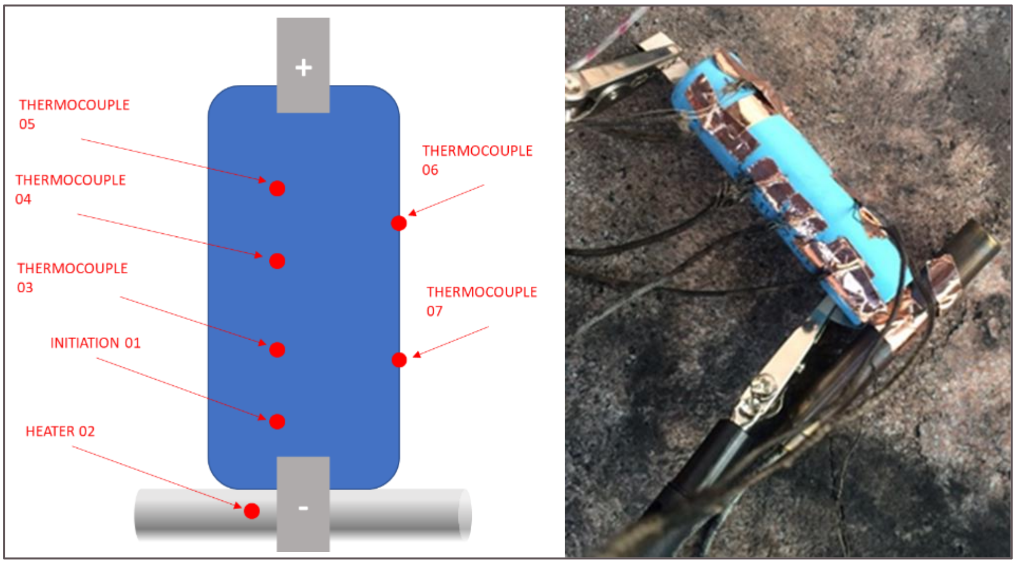

Figure 11: Cell arrangement with the heating rod at bottom of cell. The electrical connection clips for the algorithm measurement are connected to the cell tabs.

In the tests conducted with the set-up shown in Figure 11, the cell was heated until a thermal runaway occurred. The algorithm monitored the cell continuously during the heating process and calculated various parameters within the scope of tracking changes in the material and structure of the electrode. Conventional DC resistance was also recorded, but this did not significantly change until the cell went into a thermal runaway. In contrast, the algorithm detected an abnormal status of the cell appreciably earlier than when the thermal runaway occurred. This indicates that the algorithm can be considered as a good predictor for possible safety hazards that may originate from lithium batteries.

I.6.2 Thermal modelling for thermal runaway mitigation strategies

Experimental work to study thermal runaways must be carried out with safety protection against explosions and fire risks. Moreover, exploring different mitigation measures with experimental methods is expensive and time-consuming. To help to overcome these challenges, a thermal model was developed to provide guidance on the selection of mitigation measures for further experimental investigations. The thermal model developed in Task 2 was used here. The thermal numerical model provided a good understanding of the heat propagation from a thermal runaway initiation cell to the remaining cells in a box. It was also used to study the effect of different mitigation strategies for preventing the propagation of a thermal runaway.

In this study, the thermal model was applied to study different mitigation strategies for a reference case of transporting 25 cells of type 18650 (a commercially available 3.5Ah lithium-ion cell) at 100% SOC packaged in a 5x5 configuration. A cell at the corner of the cell array was simulated to instantaneously go into a thermal runaway, and the heat propagation to neighbouring cells was investigated. The cases investigated were with and without mitigation strategies. The location of the corner cell as the initiation cell was chosen as it represented the worst-case scenario in terms of the risk of abuse, as well as in terms of thermal propagation behaviour. The worst-case scenario, a corner location, was determined from the literature as well from performing simulations.

The study was performed for a base case scenario with solid fibreboard dividers between the cells to prevent the propagation of a thermal runaway. Further mitigation cases were simulated with changes in the appropriate parameters and properties from the base case as proposed improvements. A summary of the results of all the cases presented in Deliverable D3b is provided as follows:

Case Name	Mitigation Strategy	Description	Result
Case 00	None	No separators	TR for all cells
Case 01	Thin cardboard separators **BASE CASE**	Base Case of 5x5 with TR cell at a corner	TR for all cells
Case 02	Thicker cardboard separators	Base Case with 4mm separator thickness	no TR propagation
Case 03	Colder environment with higher h	Base Case with more convection heat transfer: h=50, T=0	no TR propagation
Case 04	Thin fiberboard separators	Base Case with 2mm fiberboard separators	TR for all cells
Case 05	Thin fiberboard + vermiculite	Base Case with 2mm fiberboard separators & vermiculite	TR for all cells
Case 06	Thicker fiberboard	Base Case with 2mm fiberboard separators	TR for all cells
Case 07	Thicker cardboard + vermiculite	Base Case with 4mm separator thickness & vermiculite	no TR propagation
Case 08	Sand filled cardboard box	Base Case sand filled with cells at 2mm seperation	adjacent cells vented but no TR propagation
Case 09	Alumina full container	Base Case layout in Alumina container with 4mm cell separation	no TR propagation
Case 10	Graphite full container	Base Case layout in Graphite container with 4mm cell separation	no TR propagation

From the different cases analysed, the following results can be summarised:

1. Fibreboard separators of suitable thickness were found to prevent the propagation of thermal runaway.
2. Packages placed in a colder environment with a high heat transfer coefficient can prevent the propagation of thermal runaway.
3. Thermal conductive fibreboard needs a greater thickness for TR prevention in comparison with less conductive fibreboard.
4. The presence of vermiculite instead of air is a good option when used with fibreboard separators. In addition, vermiculite will absorb any liquid that would spill from the cell after venting.

5. The use of thermally conductive material (e.g. graphite or alumina) for the construction of the packaging helps in thermal dissipation and prevents TR propagation.

Among the options identified above, the selection of appropriate materials, the thickness of the dividers between the cells, and the material used for filling the package can be considered as the most promising factors in preventing the propagation of cell-to-cell thermal runaway. Furthermore, it should be noted that the outcome from the above simulation cases is for a specific thermal runaway scenario in which one cell suddenly goes into a TR while the other cells are at room temperature. This can be considered similar to the case of a sudden nail penetration of the corner cell. If the initial conditions and the initiation conditions are changed, then some measures can either become more effective or less effective, depending on the particular case.

While the thermal model provides a good basis for qualitative assessments, it has several limitations. The simulations can be used to correctly predict the heat propagation by conduction and radiation. However, in a thermal runaway, there are other complex physics such as gas releases, flames etc. which are not fully considered in the current model. The model currently utilizes only the thermal properties of the materials to predict heat propagation. Thus, the benefits of vermiculite, for example, compared with just air, are not visible through this model. Another consideration which is important is that for dividers and packages made from fibreboard, it would be better to have a flame-resistant coating, as the temperatures can reach up to 600°C, while the flame point of most fibreboard is around 450°C. While the temperature reaching 600°C is modelled, the effect of the presence of flames is not considered in the current model.

This model was supported by the experimental data gathered in Task 2 (Phase IV tests). Figure 12 shows an example of the experimental test results obtained at Impact Solutions. A thermal runaway was induced in one of the cells (based on the "Reduced Cell Configuration" test as defined in the SAE AS1364 draft version dated November 2018), and then its propagation through the remaining cells was monitored. The cells used were at 100% SOC, and 2mm fibreboard dividers were used to separate the cells.

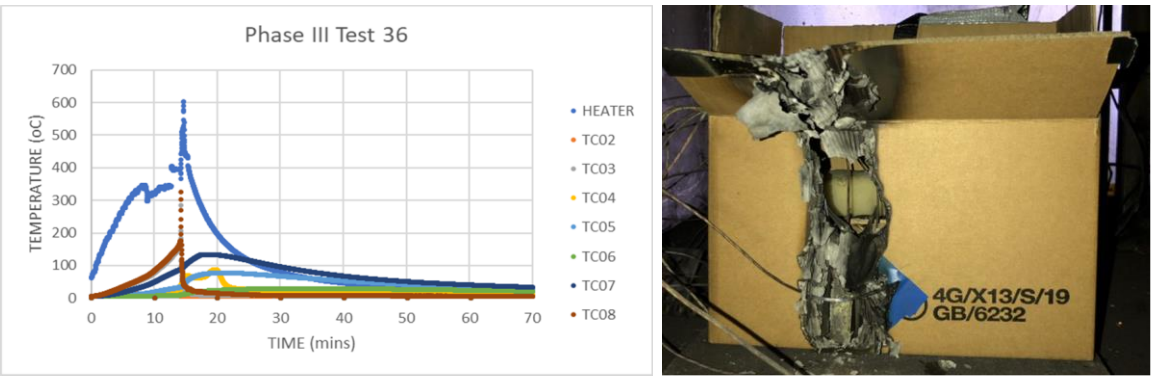

Figure 12: Picture of the package after experimental test to validate one of the modelling scenario.

Task 4: Characterisation of on-board fire protection and assessment of its contribution to the effectiveness of the proposed packaging solutions

I.7 Overview of the objectives

The fire protection systems currently installed in the Class C cargo compartments of large aeroplanes may not able to control a fire event involving lithium cells/batteries. The objective of this task was therefore to assess how the effectiveness of a state-of-the-art fire suppression system in a Class C cargo compartment could be improved through the implementation of certain mitigating measures identified in Task 2 and Task 3.

In particular, the purpose of the full-scale fire tests conducted within the scope of the Sabatair project was to assess a scenario in which lithium cells may be involved in a cargo fire initiated outside the boxes containing the lithium cells/batteries. The use of a fire containment cover (FCC), combined if necessary with a layer of thermal insulation material, was selected as a mitigating measure that could be used to prevent the involvement of the lithium cells in the external fire event. In the tests, the function of the FCC, which is normally to contain a fire developing from the cargo items inside the FCC itself, would rather be to create a protective barrier between an external cargo fire and the boxes containing the lithium cells.

The tests were performed in a test chamber representative of the design of a Class C cargo compartment installed on a large aeroplane. The test chamber has its walls, floor and ceiling made of steel, and it is equipped with an operable aircraft fire suppression system. It is important to highlight that the construction of the test chamber does not allow the evaluation of all the effects that the explosions associated with a thermal runaway event may have on Class C cargo compartments, in particular, the damage to the cargo liners that may be caused by being impacted by fragments, and the opening of decompression panels due to the pressure increase caused by an explosion.

The test plan was conceived to evaluate the external fire scenario in a 4-step approach:

1. Without activation of the aircraft fire suppression system.
2. With activation of the aircraft fire suppression system.
3. With activation of the fire suppression system and with a Fire Containment Cover (FCC) to protect the boxes in which the cells were contained.
4. With activation of the fire suppression system and with a Fire Containment Cover (FCC) combined with a layer of thermal insulation material to protect the boxes in which the cells were contained.

A detailed description of the test procedure and the results can be found in Deliverables D4a and D4b.

I.8 Brief description of the test set-up and procedure

The test chamber (*i.e.* 1:1 aircraft cargo compartment mock-up) has a volume of 56.6m^3 (see Figure 13) and was built in accordance with the Minimum Performance Standard for Aircraft Cargo Compartment Halon Replacement Fire Suppression Systems [2].

Figure 13: Photograph of the fire test chamber.

The test set-up was derived from the bulk-load fire scenario defined in the Minimum Performance Standard published by the Federal Aviation Administration (FAA). The standard was followed as closely as possible in the full-scale battery fire test. However, the arrangement of the fire load was adapted to take into account the installation limitations of the FCC.

Fibreboard boxes filled with shredded paper were used as a fire load (see Figure 14). One of the boxes was ignited by means of a resistance wire heater.

Figure 14: Fibreboard Box filled with shredded paper acting as fire source for the external fire test (left) – Fibreboard Box arrangement in the test compartment (right).

The cells tested were standard Li-ion 18650 cells from two different cell brands to represent a random mix. One of the two cell types was used in the different tests and modelling carried out during the other tasks of this project. The cells were certified to have passed UN 38.3 tests. Further details relating to the selection of cells are available in Deliverable D2a.

The cells used in the tests were arranged so that they would receive as much energy from the ignition source as possible (see Figure 15). In order to generate a sufficiently severe fire event, the cells used for the tests were either at 50% or 100% SOC. The selected values of the SOC contribute to creating critical test conditions, considering that all lithium-ion cells and batteries (UN 3480) must be shipped at a state of charge (SoC) not exceeding 30% of their rated capacity.

To monitor the generation and propagation of heat, several thermocouples were placed inside and outside the boxes (see Figure 16).

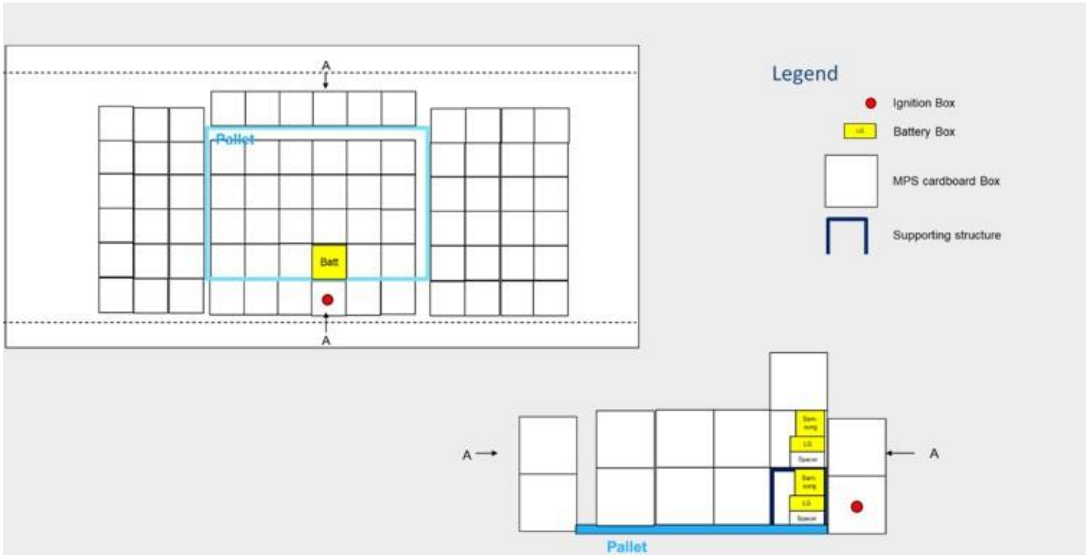

Figure 15: Arrangement of fibreboard boxes for the full-scale fire test.

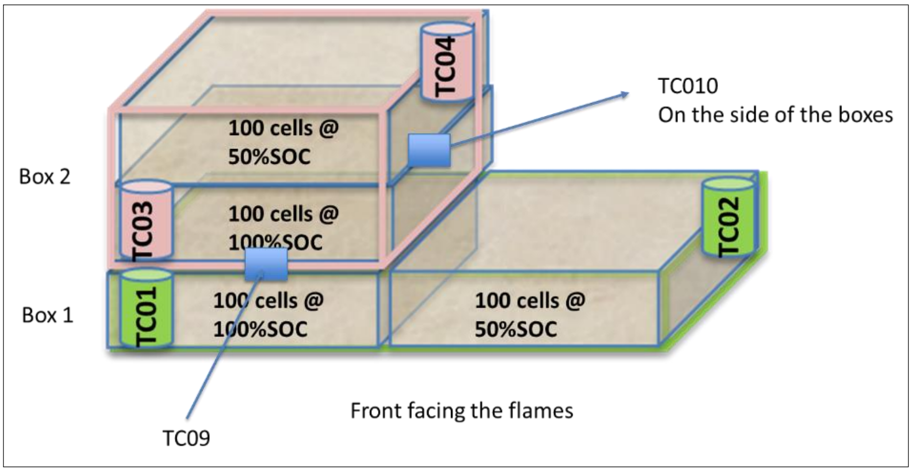

Figure 16: Position of the thermocouples of the cell packs located directly on the pallet.

I.9 Summary of the test results

The test results are summarized in the following set of charts. Each type of test described in paragraph I.7 was performed only once. The MPS test specification [2] requires every fire test scenario to be conducted at least five times in order to gather statistical relevance. Within the scope of the Sabatair Project, resources were limited, so no statistical evidence could be produced. However, the results of the tests show a clear tendency and are presented in Deliverable D4b, together with further detailed descriptions of the test results.

1. Without activation of the aircraft fire suppression system:

Several temperature measurement points directly on the cells showed readings of around 700°C. Although it was not possible to determine the exact number of cells involved in the fire event, it was estimated that around 100 cells went into thermal runaway. The cells located towards the ignition box were involved first. The test was stopped after approximately one hour. Cells were continuously reacting during this time period. Thermal runaways clearly propagated throughout the packaging boxes without any tendency for this process to self- extinguish.

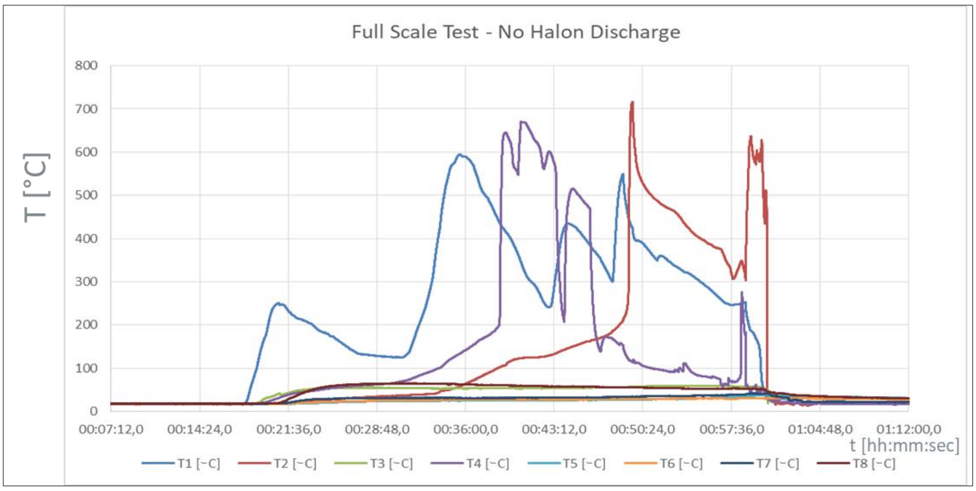

Figure 17: Temperatures during the external fire test without fire suppression.

2. With activation of the fire suppression system

The aircraft Halon Fire Suppression System was activated as soon as the temperature reading at the level of any of the cells exceeded 145 °C. The Halon eventually suppressed the propagation of thermal runaways. In the temperature profiles recorded during the test (Figure 28), it can be observed that one reading (T1 in Figure 16 and Figure 17) reached values that indicated a thermal runaway. This reading was limited to a single high peak. As the test progressed, no further temperature rise was observed at any measurement point. Most of the thermal runaway processes likely occurred before the extinguishing agent was discharged into the chamber.

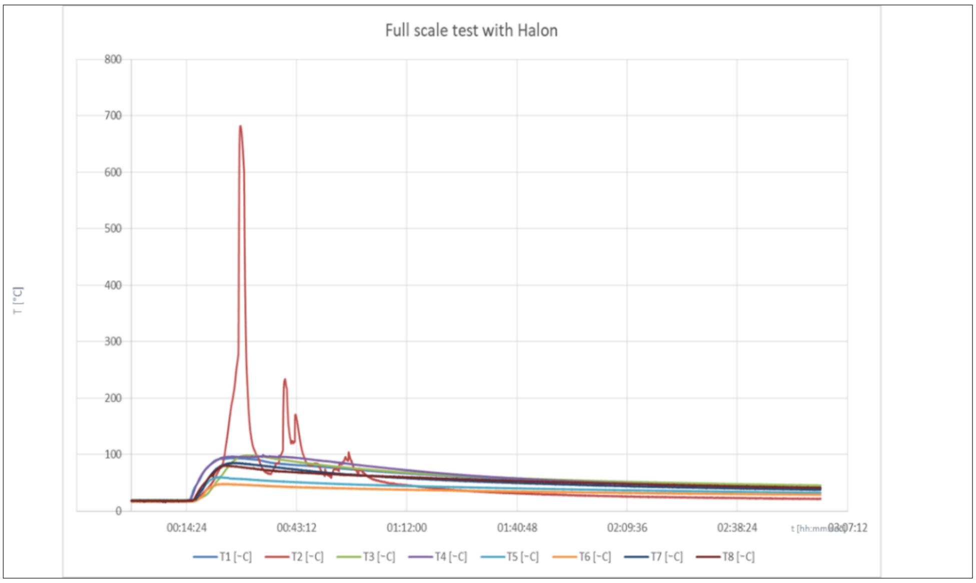

Figure 18: Temperatures during the external fire test with fire suppression.

Figure 19: Impact on Cells after the test with fire suppression.

3. With activation of the fire suppression system and a Fire Containment Cover

Adding the fire containment cover to the test set-up showed a further improvement in the results, including a significant reduction in the overall severity of the fire event. The maximum temperature observed during this test was 145°C at only one location close to the ignition box. Analysis of the impacted cells after the test showed that only one corner of one battery box was affected. The FCC itself showed burn marks, but it was not burnt through. However, the temperature levels behind the FCC were high enough to cause burn marks on the fibreboard boxes directly in contact with the rear side of the FCC.

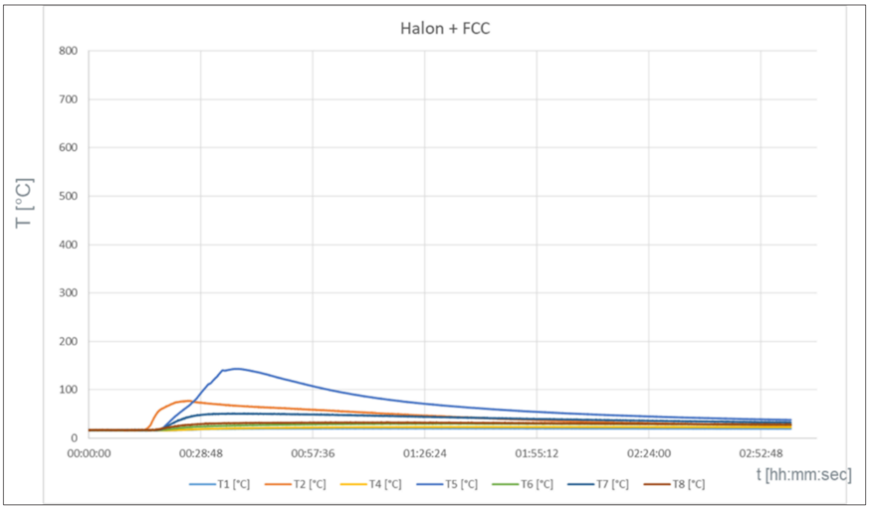

Figure 20: Temperatures during the external fire test with fire suppression and a Fire Containment Cover.

Figure 21: Fire Containment surrounded by fibreboard boxes before the test.

Figure 22: Fire Containment Cover after the test.

Figure 23: Impact on Cells after the test with Fire Suppression and a Fire Containment Cover.

4. With activation of the fire suppression system and with a Fire Containment Cover combined with a layer of thermal insulation material

Considering that in the test conducted with a Fire Containment Cover, the severity of the fire event had been reduced to an acceptable extent, no further test was performed with the addition of thermal insulation material.

Task 5: Risk assessment for the air transport of battery consignments

I.10 Overview of the objectives

The initial objective of this task was to develop a risk assessment method aimed at supporting air transport operators in defining the appropriate requirements for the safe transportation of battery consignments based on the results obtained from the previous project tasks. After coordination with EASA and the SC members, it was agreed that it was more suitable to develop risk assessment guidance. The reasoning behind this change was that air transport operators use different tools and methods and therefore one unique method cannot be imposed.

This decision to create risk assessment guidance (and not a risk assessment method) was consolidated after the workshop (Brussels, 6-7 June 2019) organised by the Sabatair project consortium on this topic. The attendees, from different parts of the lithium cell air transport supply chain, agreed on the need for guidance to help them to identify the risks related to the transportation of lithium cells/batteries and the measures needed to mitigate these risks.

I.11 Main results

The risk assessment guidance identifies the hazards and evaluates the risks, taking into account the operator's activities so that the operator can consider either removing or eliminating the hazards, and take sensible, proportionate measures to mitigate the risks to an acceptable level.

To develop the risk assessment guidance, a "3-step approach" was followed:

Step 1. The analysis and review of the results of the work carried in Tasks 1-4 led to the elaboration of an extensive list of examples that illustrate the hazards and associated potential risks to be considered by the operator during their safety risk assessment.

A process of mapping was then developed for operators carrying lithium cells, from the acceptance of a booking, to transporting and offloading the batteries at the destination (see the detailed mapping in Deliverable D5). The following seven key actors in the supply chain were identified:

- Cell/Battery Manufacturer
- Packer
- Shipper
- Freight Forwarder
- Ground Handling Agent
- Operator
- Aircraft Manufacturer

Step 2. Based on the data collected from the detailed mapping, a questionnaire was created in preparation for the Sabatair Risk Assessment for the Air Transport of Battery Consignments Workshop held in Brussels 6th to 7th June 2019. Several EU stakeholders from the lithium cell air transport supply chain (operators, ground handling agents, lithium battery experts, aircraft manufacturers …) attended the workshop, and the outcomes from the two-day workshop can be found in Deliverable D5.

Step 3. The risk assessment guidance was then created based on the outcome of the workshop. The document containing the guidance was reviewed and discussed with EASA and the SC members.

Although not all the hazards, risks and mitigating measures that are addressed in the document may be relevant for every operator, reviewing the document will certainly contribute to raising the level of awareness of the existence of certain hazards, and may give useful indications of how the associated risks may be mitigated to an acceptable level.

The operator's risk assessment and mitigating measures document should be updated periodically as new information becomes available. Based on the feedback from the air transport operator partners, the document will be updated and further improved. Its primary purpose is to provide guidance that operators can use in creating a specific safety risk assessment for lithium batteries when carried as cargo. When identifying specific hazards, evaluating risks and implementing appropriate safety risk controls in their operations, operators should give consideration to a multi-layered risk mitigation strategy. Operators need to be aware of the complexity of the supply chain. This is particularly important for areas of the world where there is a high risk of counterfeit, poor-quality or non-compliant battery shipments entering the supply chain.

These safety risk assessment guidance do not focus on or recommend the use of a specific risk assessment model or tool. Whichever model the operator chooses, the capabilities and limitations of the model need to be taken into account, including areas such as ease of use, accessibility, analytical rigour and adaptability. It is important for operators to understand that their safety risk assessment is a living document and therefore it should be kept under constant review and scrutiny to validate its effectiveness. This regular review is paramount to ensure it is still an accurate reflection of the operator's activities despite any changes that may occur within the workplace.

General conclusion

One of the main objectives of Sabatair was to assess the effectiveness of the test methods as described in the draft SAE AS6413. An initial experimental test plan was designed to evaluate the tests as described in the draft SAE AS6413. A lack of test repeatability was soon encountered. The focus was then directed to the thermal runaway initiation process. The first tests showed that a thermal runaway is strongly dependent on the type of heater used, its location on the cell surface, and the method of controlling the heating. The Sabatair test results also showed that the severity of a thermal runaway is strongly dependent on how the thermal runway is initiated. Different heating rates within the range allowed by the standard may cause the test to be either passed or failed. The test results also highlighted the importance of minimizing the amount of heat transferred from the heater to items other than the thermal runaway initiation cell, including the surrounding cells and the packaging under testing. Detailed recommendations were provided to the SAE G-27 Committee on suggested improvements to some key aspects of the test set-up definition given in SAE AS6413, such as the size of the heater, the rate of heating, and the insulation of the heater from the packaging and from cells other than the initiation cells. Ideally, the ratio of the cell/battery capacity and shape to the heating process (size and power of the heater, rate of heating) should be defined.

The second main objective of the Sabatair Project was to study and assess the effectiveness of potential mitigating measures against the fire risk related to the transportation of lithium batteries as cargo on passenger and cargo aeroplanes. The full-scale external fire tests performed during the Sabatair project showed that a state-of-the-art built-in fire suppression system of a Class C cargo compartment, combined with the use of Fire Containment Covers, could prevent the involvement of lithium cells/batteries in an external cargo fire event. However, due to the limited number of tests, statistical evidence could not be satisfactorily produced for the tested combinations of cell types, quantities and states of charge. To confirm the effectiveness of these protection measures, further investigation and repetitions of the tests would be required.

The third main objective of the Sabatair Project was to develop safety risk assessment guidance for aircraft operators. The primary purpose of this document was to provide guidance that operators can use in creating a specific safety risk assessment for lithium batteries when carried as cargo. When identifying specific hazards, evaluating risks and implementing appropriate safety risk controls in their operations, operators should give consideration to a multi-layered risk mitigation strategy. When risk mitigation measures are implemented, it is essential that the risk is not transferred. For example, addressing a solution to the identified problem should not generate or amplify another problem. Operators need to be aware of the complexity of the supply chain. This is particularly important for areas of the world where there is a high risk of counterfeit, poor-quality or non-compliant lithium batteries entering the supply chain.

Recommendations for future projects

As the SAE G27 standardization working group's focus mainly addresses the containment of a thermal event within the packaging, further research in the context of aircraft transportation is necessary to correlate the proposed packaging standard with the level of performance of the active and passive fire protection systems of an aircraft.

Early and reliable detection of lithium battery fires is still regarded as a challenging issue, and a specific solution for aircraft operator applications has not yet been found. For passenger aircraft, on which the commercial transport of lithium batteries, when shipped alone, is forbidden, having a solution that provided such detection would contribute to the relaxation or removal of this ban and would also improve the situation for freighter aircraft.

Within the Sabatair project, full-scale tests were performed with Halon 1301, which will be replaced by more environmentally friendly agents in the near future. It should be verified that the potential replacement agents provide adequate protection against the lithium battery fire threat. An extension of the MPS (Minimum Performance Standard) to include an additional fire test scenario involving the presence of lithium batteries is currently under development, and Halon replacement agents will be required to pass this test.

To date, the impact of lithium batteries contained in devices (laptops, smartphones etc.) has not been investigated. Tests could be performed to assess the risk of transportation of those devices as cargo, baggage and in the passenger cabin.

The tests in the Sabatair project were performed with rechargeable lithium-ion cells. It would also be useful to conduct similar investigations on lithium-metal cells (primary cells) and to re-assess the results of the Sabatair project for those cells.

Although the scope of this project did not include them, PEDs (Personal Electronic Devices) carried by passengers or aircraft crew in the cabin are recognized as a potential fire, smoke and explosion risk. The limits on the quantity and on the power (Wh/lithium content) of the PEDs allowed on board are based on the PEDs that passengers normally carry rather than on scientific evidence, and there is therefore no information on how the potential consequences of an event are related to such factors. The effects on PEDs caused by the environmental conditions typical in large aeroplanes is also unknown. Additionally, an assessment of the consequences of large amounts of smoke in the cabin could be conducted to propose solutions to this risk. Lastly, emergency procedures could be challenged and improved. Existing and new solutions should be explored and used to improve the efficiency of the handling and the suppression/containment of fires, both in the passenger cabin and in the cockpit.

Status of deliverables

Del. no.	Deliverable title	Task no.	Nature, Scope	Dissemination level	Final version	Status
D0	Project Management Plan (PMP)	N/A	Report	PU	T0 + 1m	Submitted
D1a	Review of the state-of- the-art for lithium battery fire – explosion – smoke risks and associated mitigating measures	1	Report	PU	T0 + 2m	Submitted
D1b	Hazard Identification and Characterisation	1	Report	PU	T0 + 3m	Submitted (D1a and D1b were merged in one document)
D1c	Detailed technical work plan	1	Plan	PU	T0 + 3m	Submitted
D2a	Test plan for packaging effectiveness	2	Report	PU	May 2020	Submitted
D3a	Test plan for additional mitigating measures	3	Report	PU	July 2019	Submitted
D2b	Test report for packaging 'Assessment of the effectiveness of the packaging performance tests'	2	Report	PU	April 2020	Submitted
	Summary interim progress report		Report	RE	T0 + 12 m	Submitted January 2019
D3b	Test report for additional mitigating measures	3	Report	PU	May 2020	Submitted
D4a	Lithium ion cell exposure to an on-board external fire: Test Program	4	Report	PU	May 2020	Submitted Not official deliverable but its creation was requested by EASA
D4b	Test report for impact of on-board fire-protection capabilities	4	Report	PU	April 2020	Submitted
D5	Initial Risk Model (including solely the packaging)	5	Report	RE	May 2020	Submitted

Del. no.	Deliverable title	Task no.	Nature, Scope	Dissemination level	Final version	Status
	'Baseline of Air Transport Operators Generic Safety Risk Assessment Guidance for the Safe Transport of Battery consignment as Cargo'					
D6	Consolidated Risk Model (covering all proposed mitigating measures) 'Air Transport Operators Generic Safety Risk Assessment Guidance for the Safe Transport of Lithium Battery'	5	Report	PU	May 2020	Submitted
D7	Draft Final Report	6	Report and presentation	RE	May 2020	Submitted
D8	Final report	6	Report and presentation	PU	T0 + 21m	
D9	Final report – technical assistance activity.	7	Report	RE	T0 + 24m	