SABATAIR

Deliverable 2a:

Identification of packaging solutions and assessment of their effectiveness

Task	**2**	Identification of packaging solutions and assessment of their effectiveness

Dissemination level[1]	CO	**Due delivery date**	30/06/2018
Nature[2]	R	**Actual delivery date**	07/05/2020

Lead beneficiary	**IMPACTSOLUTIONS**
Contributing beneficiaries	VITO, ALGOLION

Document Version	**Date**	**Author**	**Comments**[3]
V0.1	28/5/2018	S. Burns (IMPACT)	Creation
V0.2	30/5/2018	S. Burns	Revisions
V0.3	31/5/2018	S. Burns	Revisions
V1.0	1/6/2018	S. Burns	For dissemination
V1.2	18/9/2018	D.Finlayson	FINAL_old
V1.3	1/10/2018	S.Burns	Revisions
V1.4	23/10/2018	VITO	Revisions
V1.5	4/12/2018	S.Burns	Revisions

[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

V1.6	04/01/2019	VITO & S.Burns	New document with new chapters
V1.7	26/05/2019	Paul Horner (External reviewer)	Review and revisions
V1.8	18/06/2019	Khiem Trad (VITO)	Revisions
V1.9	13/08/2019	Khiem Trad & Steven Burns	Revisions after Enzo's review and comments
V2.0	04/05/2020	Enzo Canari (EASA)	Final Review
V2.1	07/05/2020	Khiem Trad (VITO)	Final version

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Introduction

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 pertains only to Lithium-ion batteries shipped as cargo on passenger aircraft, and not to those contained in personal electronic devices carried by passengers or crew. It comes subsequent to extensive reviews undertaken by the ICAO Air Navigation Commission, and the UN agency'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 decided that batteries under the UN 3090 and UN 3480 classification (lithium metal and lithium ion cells or batteries) be forbidden for transport as cargo on passenger aircraft. This is a temporary measure until controls are put in place to establish an acceptable level of safety. ICAO requested that the SAE International Standards organization create a standardization 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.

The packaging standard is under development by SAE International and is known as the 'G-27 Lithium Battery Packaging Performance Committee' (SAE reference number AS6413). The SAE G-27 committee is comprised of representatives from ICAO, International Air Transport Association (IATA), International Federation of Airline Pilots Association (IFALPA), International Coordination Council for Aerospace Industry Association (ICCAIA), European Association for Advanced Rechargeable Batteries (RECHARGE), Rechargeable Battery Association (PRBA), Battery Association of Japan (BAJ), European Aviation Safety Agency (EASA), defence agencies, aircraft operators/airlines, packaging manufacturers and regulatory authorities [1]. Addendum No. 4 to the 2015-2016 Edition of the Technical Instructions prohibits the transport of lithium ion batteries as cargo on passenger aircraft as a temporary measure until controls are 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 (G-27 Standard);
2) The creation of guidance and supporting material for air operators that could be used for their safety risk assessments that could support bulk shipment when transporting lithium batteries on aircraft;
3) Develop additional operational controls to mitigate aviation specific risks posed by lithium batteries including a mechanism to identify and communicate specific hazards associated with different battery types and to ensure transparency of shipments including those not subject to full regulation;
4) Introduce measures to reduce levels of non-compliance.

The SAE AS6413 (Performance based packaging standard) will provide a test method and protocol to ensure that the hazards from lithium metal batteries (UN 3090) and lithium ion batteries (UN 3480) are contained within a package in the event of a thermal event. The standard has the objective to simulate and evaluate the consequences of an event in which a single cell may enter thermal runaway during transport.

Therefore, controlling the consequences of a cell or battery failure within the package will prevent uncontrolled fire and pressure pulses that may compromise the effectiveness of fire suppression systems installed on Class C cargo compartments.

The objective of Task 2, as initially published in the tender, was to identify packaging solutions and to assess their effectiveness by performing a series of tests based on the content of the draft SAE AS6413. However after the start of the SaBatAir project, the main objective of Task 2 has become to evaluate the SAE AS6413 draft standard by building the test equipment, test setup and performing a series of tests in accordance with this standard. Where necessary, thermal modelling will be carried out to complement experimental tests which have been conducted.

Chapter I contains a review of existing standards/regulations related to the transport of dangerous goods by air.

Chapter II is a review of existing packaging solutions commonly used to transport dangerous goods.

Chapter III introduces the SAE AS6413 standard describing the different tests and procedures that will be evaluated in Task 2. Based on the information that is provided in the November 2018 draft of the SAE AS6413 standard, whose content is described in Appendix B, the test procedures, test rig construction and apparatus needed to perform the tests will be detailed. This is then supplemented by a description of the test program (ref. Table 5) and by the decision flow chart for changes to the test program reported in Appendix A.

Chapter IV gives an introduction and a description of the thermal modelling work planned for this task. In this study, thermal modelling assists the experimental tests by giving inputs, *e.g.* the optimum position of a thermocouple. Once the thermal model is validated, simulation can be made on scenarios that will not be tested. For example, tests using pouch cells. An overview of how the model functions and what outputs that can be collected and evaluated are described.

Chapter I: Dangerous goods transport regulatory environment

Lithium batteries are classified as dangerous goods for transport. Because of the dangers of thermal events, including fire, explosion and off-gassing, lithium ion batteries are subject to complex transport and other regulations for their manufacture, testing and classification. For transportation by any mode of transport, packaging provisions must be complied with together with package labelling and marking. Dangerous goods transport documents must accurately reflect the contents of a shipment and quantities being shipped; handling requirements also apply. For example, they must be segregated from certain other flammable dangerous goods during air transport. The aircraft captain should be notified of the quantity, type and the location of dangerous goods on board the aircraft. The scope of the SaBatAir project is to consider lithium batteries shipped alone as cargo.

I.1 United Nations

I.1.1 Section 38.3 of the Manual of Tests and Criteria

The United Nations regulations for transport testing of lithium metal and lithium ion batteries are covered under UNECE section 38.3 of the UN Manual of Tests and Criteria. Lithium metal and lithium ion batteries are designated as Class 9 materials according to the UN Dangerous Goods Classification system (see Table 1), meaning that they present a hazard during transportation.

With the exception of prototype lithium batteries and some small production runs, all lithium batteries are required to pass section 38.3 of the UN Manual of Tests and Criteria (UN Transportation Testing). Section 38.3.4 provides details of the 8 tests:

- T.1: Altitude simulation;
- T.2: Thermal test;
- T.3: Vibration;
- T.4: Shock;
- T.5: External shore circuit;
- T.6: Impact/crush;
- T.7: Overcharge;
- T.8: Forced discharge.

The tests are intended to represent transport conditions, including those for air transport. Details of the tests can be found in Revision 6 of the UN Manual of Tests and Criteria - https://www.unece.org/fileadmin/DAM/trans/danger/ST_SG_AC.10_11_Rev6_E_WEB.pdf

Table 1: UN classification of dangerous goods and ICAO packaging instructions/ lithium batteries.

UN Number	Substance	Hazard Class	ICAO Packaging Instruction Number
3480	Lithium ion cells and batteries (including lithium ion polymer)	9	965
3481	Lithium ion cells and batteries contained in or packed with equipment	9	966 967
3090	Lithium metal (including lithium alloy) cells and batteries	9	968
3091	Lithium metal cells and batteries contained in or packed with equipment	9	969 970

I.1.2 UN dangerous goods packaging testing

The United Nations recommendations are the basis for dangerous goods regulations used by all modes of transportation, including the ICAO Technical Instructions for the Safe Transport of Dangerous Goods by Air. The IATA Dangerous Goods Regulations are a user friendly version of the ICAO Technical Instructions which also includes additional industry requirements. The UN Model Regulations specifies in Part 6: "Requirements for the construction and testing of packaging, intermediate bulk containers, large packaging, tanks and bulk containers", the types of packaging, the limits that can be used and the testing requirements for the packaging to be certified.

The tests listed by Part 6 are:

1. Drop Test:
   This involves dropping a package as prepared for transport from a varying height at different drop attitudes, depending on the material of construction (type), the contents to be carried, and the packing group of the contents (determined from the UN numbers or other data (for example Safety Data Sheets)). A pass is obtained if no physical leakage of the contents is visible from the outside of the packaging.
2. Internal pressure (hydraulic) test
   These are relevant only for packages containing liquids and therefore not discussed with regard to batteries.
3. Stacking test
   This test requires a package as prepared for transport to be stacked with a force on top of the package equivalent to the total weight of identical packages which might be stacked on the test package during transportation. The minimum test height is 3 metres and the duration of the test is 24 hours (for plastic packaging intended for liquids, the duration is extended to 28 days) at a temperature of not less than 40°C. The stack may not collapse during the test, nor should there be leakage from the

test package. The test does not require dangerous goods to be in the package and a suitable placebo may be used instead.

Part 6 contains no specific measures for certification of packages intended to carry Class 9 lithium batteries.

I.1.3 UN Special Provision 188

Transport of lithium batteries that are compliant with Special Provision 188 of the UN Recommendations (adopted in the ADR/IMDG (road and sea) Regulations) are not subject to other provisions of the applicable regulations and can be transported as "Excepted" lightly regulated lithium batteries. The Special Provision (SP) is the basis for Sections IB and II of the ICAO/IATA requirements (see **Figure 1Error! Reference source not found.** and **Figure 2Error! Reference source not found.**) shown in ICAO/IATA Packing Instructions 965 and 968. ICAO/IATA Packing Instructions 965 and 968 includes additional restrictions for air transport. This includes limits on the number of cells or batteries and the maximum net weight and number of packages for Section II. A lower maximum net weight and additional marking and labelling and documentation requirements for Section IB (see **Figure 1Error! Reference source not found.** and **Figure 2Error! Reference source not found.**). SP 188 states that lithium cells/batteries are not subject to other ADR provisions if they meet all of the following requirements [2]:

1. Lithium equivalent content is less than 1g for a lithium metal/lithium alloy cell, and for a lithium ion cell, the Watt-hour rating is not more than 20Wh;
2. The aggregate lithium content is not more than 2g for lithium metal battery, and for a lithium ion battery, the Watt-hour rating is not more than 100Wh;
3. Each cell is of a type approved under UN Manual of Tests and Criteria, Part m, sub-section 38.3;
4. Cells are separated so as to prevent short circuits and packaged in strong materials;
5. Each package shall be marked with the appropriate lithium battery mark. This requirement does not apply to:
    a. Packages containing only button cell batteries contained in equipment (including circuit boards); and
    b. Packages containing no more than four cells or two batteries installed in equipment, where there are not more than two packages in the consignment;
6. Except when batteries are installed in equipment, each package shall be capable of withstanding a 1.2m drop test in any orientation without damage to cells or batteries contained therein, without shifting of the contents so as to allow battery to battery (or cell to cell) contact and without release of contents; and
7. Except when batteries are installed in or packed with equipment, packages shall not exceed 30 kg gross mass.

Note. "lithium content" means the mass of lithium in the anode of a lithium metal or lithium alloy cell.

I.2 International Civil Aviation Organization (ICAO)

The regulatory environment for the transport of lithium batteries continues to evolve. Regulatory agencies around the world are moving towards consistent international regulations and best practices for the transport of shipments containing lithium batteries, in the main based on the UN Recommendations for the Safe Transport of Dangerous Goods. The most recent significant regulatory changes for air transport came when ICAO amended the 2015/2016 Edition of the Technical Instructions for the Safe Transportation of Dangerous Goods by Air (ICAO Addendum No. 3 January 15, 2016; ICAO Addendum No. 4, February 23, 2016) to include:

1. A prohibition on the transport of lithium ion batteries shipped alone when carried as cargo aboard passenger aircraft (unless contained in or packed with equipment).
2. Lithium ion batteries shipped alone (UN3480) for transport in cargo aircraft be limited to a state-of-charge not exceeding 30% of their rated capacity.

The ICAO Council prohibited the transport of lithium batteries as cargo on passenger aircraft as a temporary measure until controls were put into place which established an acceptable level of safety. A performance-based packaging standard was identified as one of the controls. SAE International was chosen to lead this effort through the creation of an SAE Aerospace standard.

I.2.1 Packing instruction 965 – UN3480 Lithium ion batteries (see Figure 1)

General Requirements

The following requirements apply to all lithium ion or lithium polymer cells and batteries:

1. Cells and 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 (e.g. those being returned to the manufacturer for safety reasons);
2. Waste batteries and batteries being shipped for recycling or disposal are forbidden from air transport unless approved by the appropriate national authority of the State of origin and the State of the operator;
3. Cells and batteries must be protected so as to prevent short circuits. This includes protection against contact with electrically conductive materials within the same packaging that could lead to a short circuit.

Section IA applies to lithium ion cells with a Watt-hour rating in excess of 20Wh and lithium ion batteries with a Watt-hour rating in excess of 100Wh, or to quantities of lithium ion cells or batteries in excess of those permitted in Section IB of this packing instruction which must be assigned to Class 9 and are subject to all of the applicable requirements of these Regulations;

Section IB applies to lithium ion cells with a Watt-hour rating not exceeding 20Wh and lithium ion batteries with a Watt-hour rating not exceeding 100Wh packed in quantities that exceed the allowance permitted in Section II, Table 965-II; and

Section II applies to lithium ion cells with a Watt-hour rating not exceeding 20Wh and lithium ion batteries with a Watt-hour rating not exceeding 100Wh packed in quantities not exceeding the allowance permitted in Section II, Table 965-II.

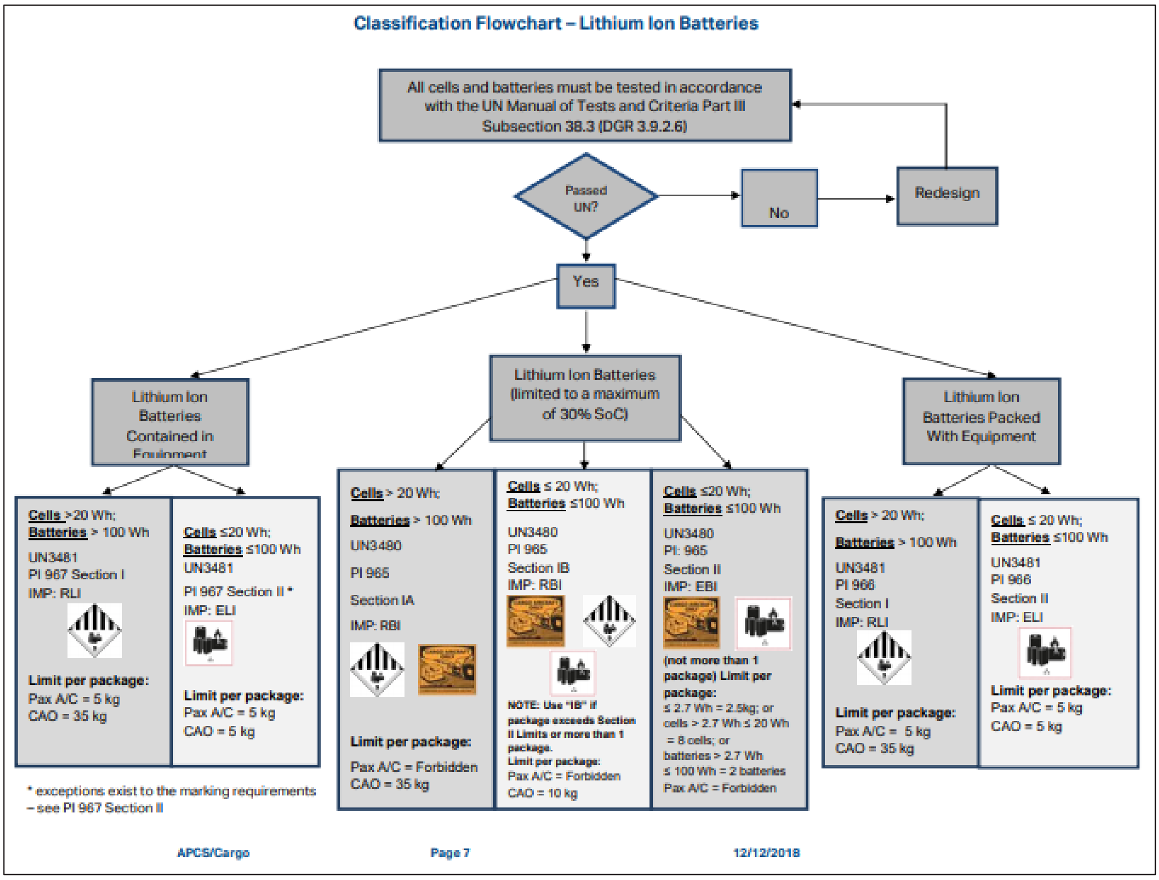

Figure 1: Flowchart of ICAO/IATA requirements for Li-ion batteries [3].

I.2.2 Packing instruction 968 – UN3090 Lithium Metal Batteries (see Figure 2)

General Requirements

The following requirements apply to all lithium metal or lithium alloy cells and batteries:

1. Cells and 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 (e.g. those being returned to the manufacturer for safety reasons);
2. Waste batteries and batteries being shipped for recycling or disposal are prohibited from air transport unless approved by the appropriate national authority of the State of origin and the State of the operator;

3. Cells and batteries must be protected so as to prevent short circuits. This includes protection against contact with electrically conductive materials within the same packaging that could lead to a short circuit.

Section IA applies to lithium metal cells with a lithium metal content in excess of 1 g and lithium metal batteries with a lithium metal content in excess of 2 g, or to quantities of lithium metal cells or batteries in excess of those permitted in Section IB of this packing instruction which must be assigned to Class 9 and are subject to all of the applicable requirements of these Regulations;

Section IB applies to lithium metal cells with a lithium metal content not exceeding 1 g and lithium metal batteries with a lithium metal content not exceeding 2 g packed in quantities that exceed the allowance permitted in Section II, Table 968-II; and

Section II applies to lithium metal cells with a lithium metal content not exceeding 1 g and lithium metal batteries with a lithium metal content not exceeding 2 g packed in quantities not exceeding the allowance permitted in Section II, Table 968-II.

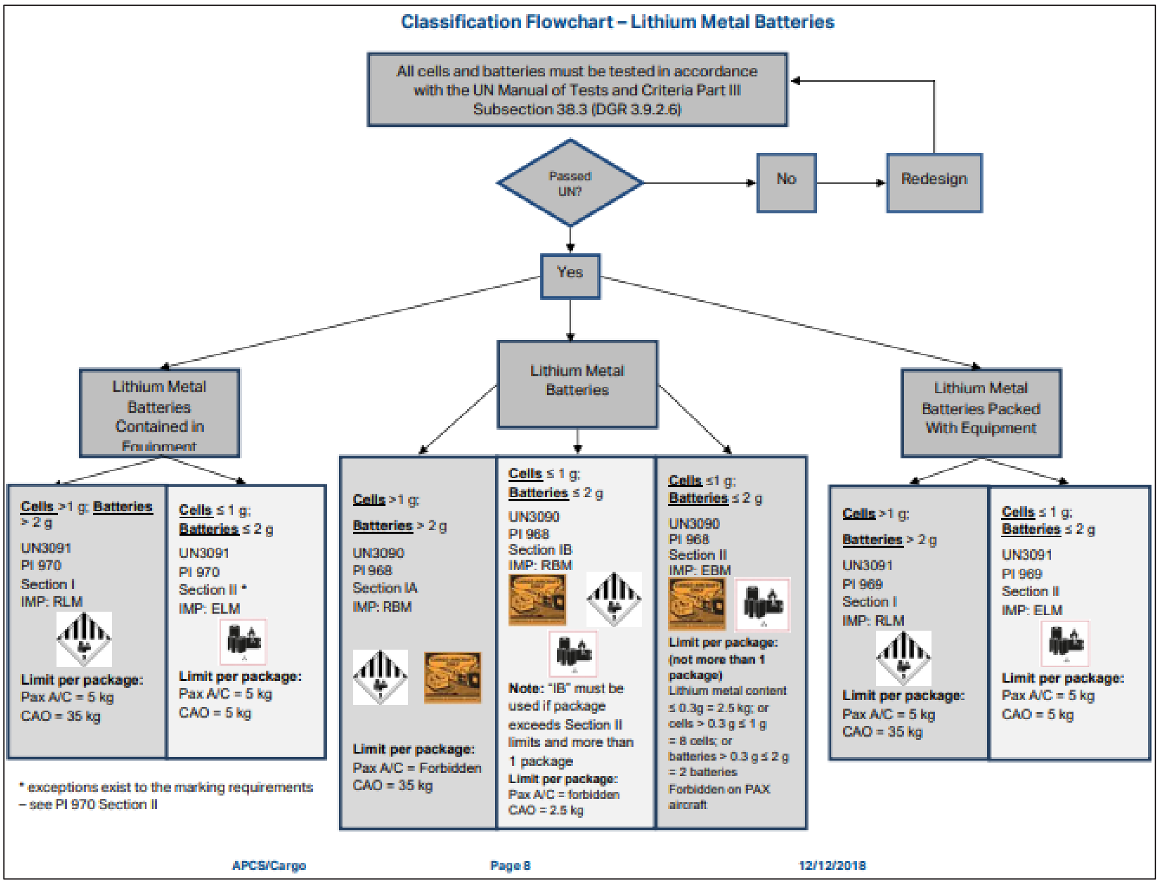

Figure 2: Flowchart of ICAO/IATA requirements for lithium metal batteries [3]

I.3 SAE and the G-27 Committee

The SAE established the G-27 Committee for Lithium Battery Packaging Performance in March 2016 to create a performance-based package standard (SAE Aerospace Standard AS6413) for the safe transport of lithium batteries when shipped alone (UN3090 and UN3480) as cargo for air transport. The standard being drafted, “Performance based package standard for lithium batteries as cargo on aircraft” (AS6413), will specify the minimum package performance standard that provides for the safe shipment of lithium batteries as cargo on aircraft.

The SAE AS6413 Standard will provide criteria which must be met for a lithium battery fire event to be contained within a package, and for the associated off-gassing not to generate explosions that would compromise the effectiveness of the cargo compartment fire protection systems. Work is also underway to develop criteria to mitigate the risk of an external fire from other cargo. More details about this draft standard will be discussed later in this document.

I.4 IEC 62281:2019 Safety of primary and secondary lithium cells and batteries during transport

The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The IEC International Standard IEC 62281:2019 specifically addresses the safety of primary and secondary lithium cells and batteries during transportation other than for recycling or disposal. This standard is considered by ICAO as “a useful reference in and supplement to the Technical Instructions in terms of providing useful and accessible information to shippers and carriers, but should not be viewed in any way as an alternative to the Technical Instructions”.
The IEC 62281 contains transport tests (altitude, thermal cycling, vibration, shock, external short-circuit and impact), misuse tests (overcharge, forced discharge) and packaging tests (drop test).

I.5 International safe transit association (ISTA)

ISTA has devised a number of standards to qualify packaging for safe shipments. The standards are almost exclusively built around whether any damage is caused to the materials being shipped during the testing, with the testing protocols requiring qualification checks on packaged materials.

Therefore they are used extensively by shippers of goods deemed to be delicate or expensive. While ISTA is a USA based body, the Certified Packaging Laboratory Professional (CPLP) certification is accepted worldwide.

The ISTA testing regulations are split into 7 “series” which cover a wide range of different packaging sizes, types (materials) and configurations. The first 3 series are the most commonly used. These are:

ISTA 1 Series: Non-Simulation Integrity Performance Tests. These challenge the strength and robustness of the product and package combination. They are not designed to simulate environmental occurrences. They are useful as screening tests, particularly when used as a consistent benchmark over time.

ISTA 2 Series: Partial Simulation Performance Tests. These are tests with at least one element of a 3 Series type General Simulation performance test, such as atmospheric conditioning or mode-shaped random vibration, in addition to basic elements of a 1 Series type Non-Simulation Integrity Test.

ISTA 3 Series: General Simulation Performance Tests. These are designed to provide a laboratory simulation of the damage-producing motions, forces, conditions, and sequences of transport environments. They are applicable across broad sets of circumstances, such as a variety of vehicle types and routes, or a varying number of handling exposures. The characteristics will include simple shaped random vibration, different drop heights applied to the sample package, and/or atmospheric conditioning such as tropical, wet or winter/frozen.

None of the ISTA series specifically cover lithium batteries, however many of the tests are those stipulated by the range of battery only tests reported in deliverable D1.

I.6 Other standards

Another standards outside the ISTA and UN requirements is set by American Society for Testing and Materials (ASTM) and are described by ISTA as:

- D4169 (Standard Practice for Performance Testing of Shipping Containers and Systems) This standard provides a guide for the evaluation of shipping units in accordance with a uniform system, using established test methods at levels representative of those occurring in actual distribution. The recommended test levels are based on available information on the shipping and handling environment and current industry/government practice and experience. The tests should be performed sequentially on the same containers in the order given. For use as a performance test, this practice requires that the shipping unit tested remain unopened until the sequence of tests are completed. If used for other purposes, such as package development, it may be useful to open and inspect shipping units at various times throughout the sequence. This may, however, prohibit evaluating the influence of the container closure on container performance.
- D7386 (Standard Practice for Performance Testing of Packages for Single Small Parcel Delivery Systems) is a relatively new (2008) General Simulation test specific to the small parcel distribution environment [4].

Neither of these standards deals specifically with lithium batteries and repeat many of the tests described in Deliverable 1 of the present study.

Within ISO, the standards are set by a technical committee 122 [5]. TC/122 has currently published 83 standards on packaging, with a further 14 currently in review/draft stage; none of these standards cover lithium batteries.

Chapter II: Review of existing packaging solutions for Lithium batteries

To review the packaging solutions for lithium batteries, it is worthwhile to begin the discussion by classifying the batteries. The flow charts shown earlier (**Figure 1Error! Reference source not found.** and **Figure 2Error! Reference source not found.**) provide guidance on the classification of lithium ion and lithium metal cells and batteries for air transport [3].

II.1 4G or 4GV UN approved boxes

UN specification packagings are marked to indicate that the packaging has been successfully tested to a design type and that it complies with the provisions of Subsection 6.2 and 6.3 of the IATA Dangerous Goods Regulations. These are related to the manufacture, but not to the use, of the packaging. Therefore, the marks do not necessarily confirm that the packaging may be used for any particular substance.

The term 4G is an example of a packaging code that forms part of this mark. In this case, 4G indicates the packaging is a fiberboard box. These UN approved boxes cover the regulations set out by ICAO, IATA, the United States Code of Federal Regulations title 49 which concerns transportation (CFR-49), the International Maritime Organization (IMO) and the International Maritime Dangerous Goods Code (IMDG) [6]. All UN 4G products bear a symbol which indicates they have been successfully tested to a design type and are acceptable for use with certain dangerous goods by sea, land and air.

UN certified 4G boxes are only suitable in combination with the specific inner packaging with which they have undergone tests. The letter “V” may follow the packaging code, this signifies a “Special Packaging” conforming to the requirements in IATA Dangerous Goods Regulations 6.3.1.2 (Exemption from testing). For example, a UN certified 4GV box may be used for shipping articles or inner packaging of any kind, for liquids or solids of packing group I, II, III, providing the requirements of IATA Dangerous Goods Regulations 6.3.1.2 are complied with. **Figure 3** shows an example of a UN 4G fibreboard box.

Figure 3: Example of an UN approved fiberboard box to transport lithium batteries

II.2 Plastic packagings

Plastic packagings include drums, jerricans or boxes may be made using flame retardant ABS materials or similar. The UN and ICAO/IATA currently allow the use of plastic packagings for both fully regulated and lightly regulated lithium battery shipments (see for example ICAO/IATA Packaging Instruction 965). During thermal runaway, the plastic may melt and cause a failure, regardless of its flame retardancy. Also, testing should differentiate between reaction to flame and possible reaction to heat.

II.3 Metallic containers

These containers use multi walls, with air gaps, to contain the heat produced by any thermal runaway. The tops are sealed with pressure fittings to contain gases.
Little literature regarding these containers ability to contain the fire risk by using a "box within a box" to limit the spread of heat, while using a sealed system which will retain gases given off, is available. The box does protect against the ejection of projectiles and flames from an exploding cell.

II.4 Flexible containers

Fabric containers (see Figure 4) are another possible solution for battery transportation. While not marketed specifically as a storage or transportation system for lithium batteries, the packaging is designed to withstand internal or external fires. These type of packages have to be used in combination with other packaging or over pack solutions.

Flexible packagings are currently not permitted under the regulations, however they would be allowed for use as an external or intermediate packaging to contain an event or external fire protection. If applied externally by the shipper, this would be considered an "overpacks" in the ICAO TI.

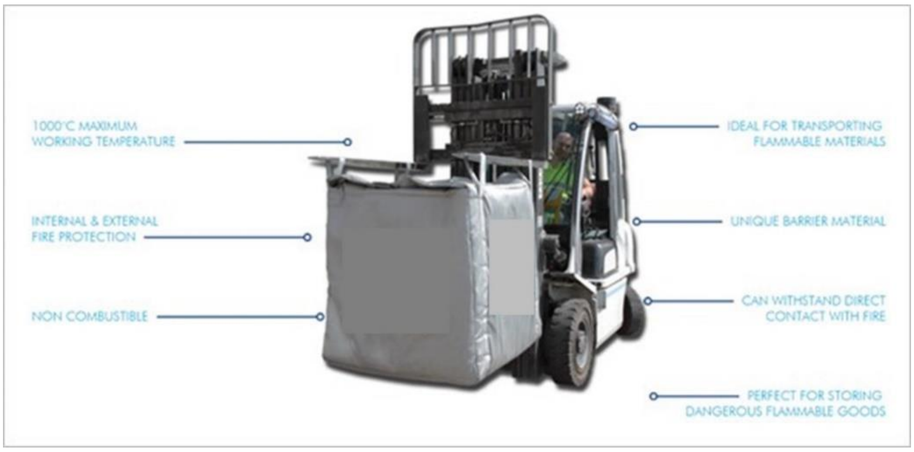

Figure 4: Example of flexible container

II.5 Identification of materials to be considered in packaging design

A fault tree was created and reported in deliverable D1 to predict the battery failure modes of the packaging. Different packaging solutions and how these may lead to a failure have been considered.

Packaging methods and factors affecting failure can be summarized as:

1. Size (cell shape and size) and spacing (distance) of packaged cells.
2. Quality control procedures of the packaging material (consistency). How the packaging can retain the exothermic onset temperature of a battery (thermal properties and thickness).
3. Flammability of the material.
4. Container sealing quality.
5. Distance between cells and side wall of packaging.
6. Quality of box wall (thickness/strength).
7. Other mitigation systems potential interactions (cooling gas, gels, gas absorbers, heat absorbers, detectors, etc.).

The materials selected for a safe packaging design should consider all of the above as a minimum.

Chanson [7] previously carried out work on the performance of packaging design for the thermal runaway of lithium ion cells. In the study, Chanson looked at a number of inner packaging materials commonly used to comply with UN packaging instruction P908 (this is specialised packaging for damaged/defective cells/batteries, not used for routine transport, where IATA PI 965 and 968 apply) which states: *"Each inner packaging shall be surrounded by sufficient non-combustible and non-conductive thermal insulation material to protect against dangerous evolution of heat" – UN manual P908*

As Chanson notes, there is no information provided on what material would meet this criteria. The study considered the insulation properties of different packing materials (see Figure 5).

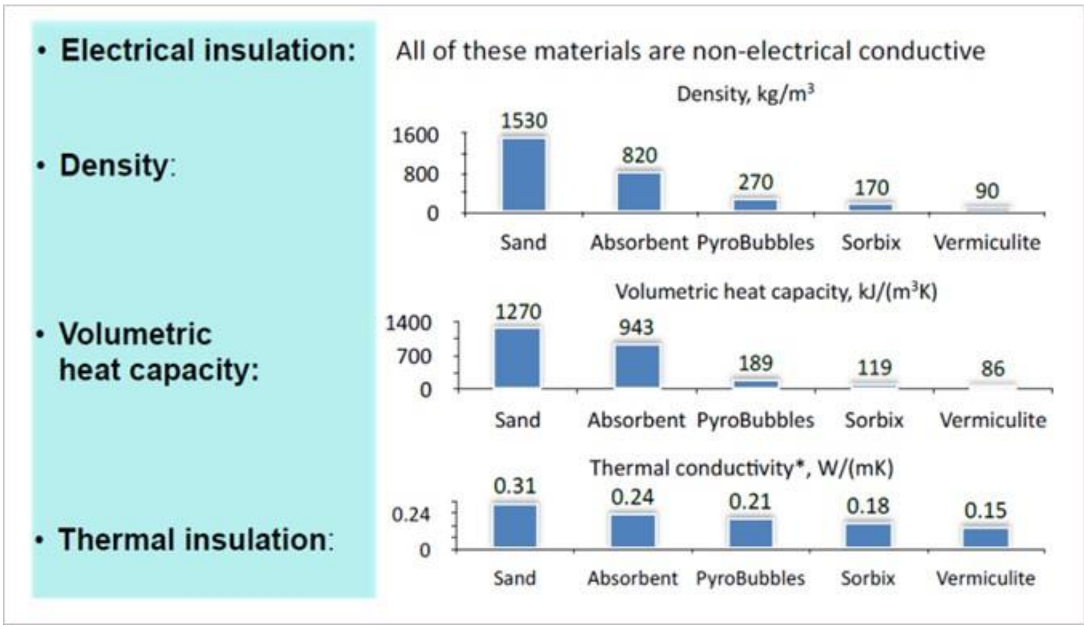

***Figure 5: Insulation properties of different inner packaging materials** [8]*

A heater plate was attached to a lithium ion cell which was placed into a medium of the above inner packaging solutions. Thermocouples were placed 15mm from the battery and monitored the temperatures measured as the cell was placed into thermal runway. This is summarised in Figure 6;

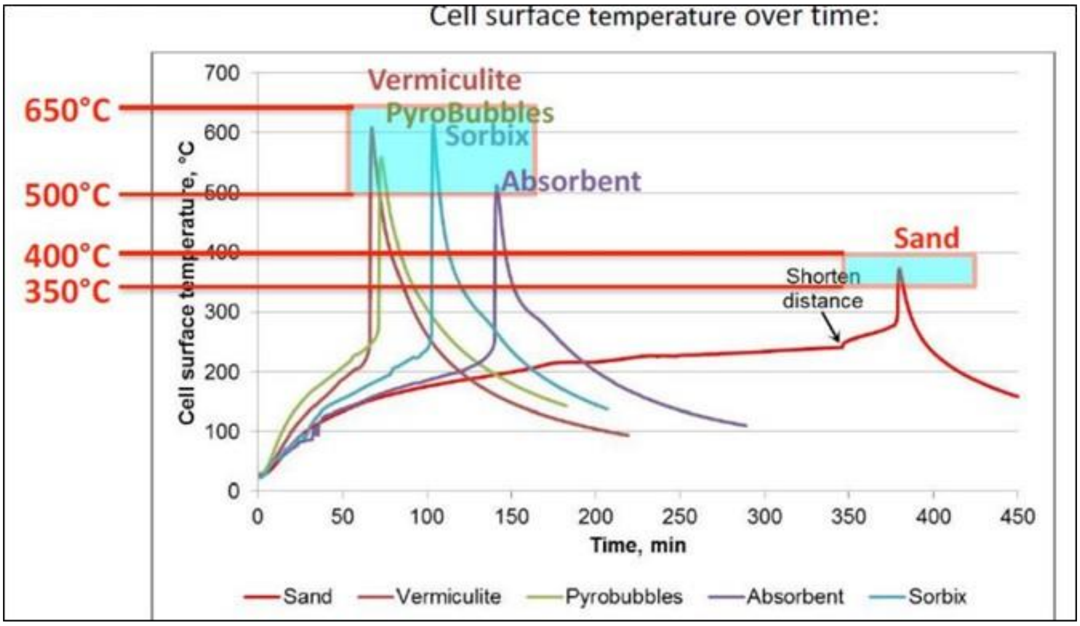

Figure 6: Temperature observed *[7]*

Using the information obtained at this stage, Chanson was able to model the minimum safe distance required between cells using each different medium as the separator (see **Figure 7**).

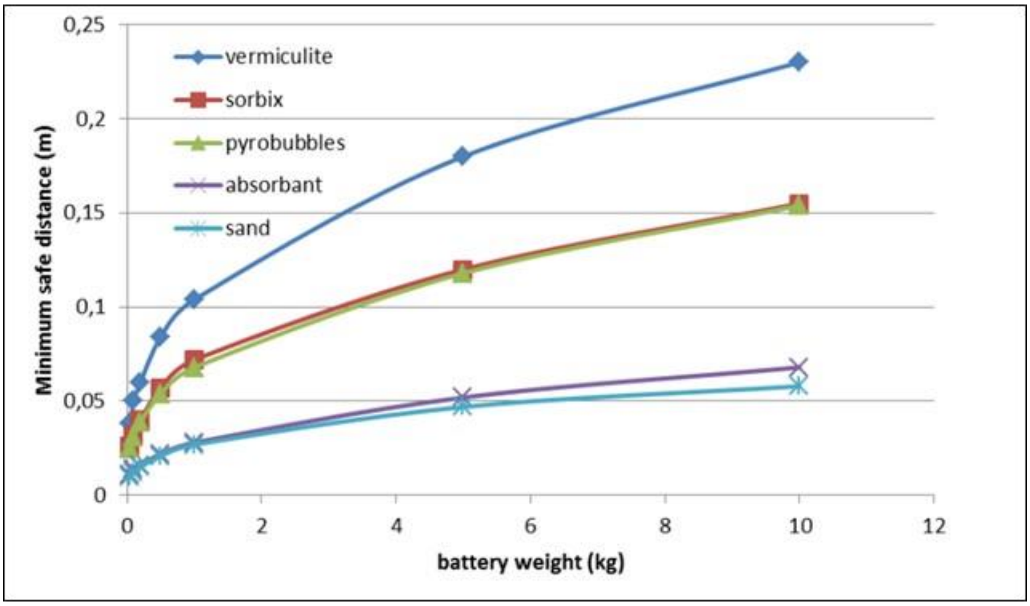

Figure 7: Minimum safe distance per inner material *[7]*

The report concludes that based on the number of cells in the packaging, a percentage by weight of cushioning material should be used.

Mineral wools

While marketed for use in construction, there are a number of mineral wools on the market that are used for flame retardancy and insulation. An example is the product shown in Figure 8, which is made with a material that can withstand temperatures of 750°C when tested under ASTM E136. This type of material could be used as an alternative to vermiculite or as a barrier material within another packaging solution.

It may be possible that a hybrid container, using a variety of the materials above, could offer the best solution to mitigate transportation of lithium ion batteries.

There are a number of other commercially available products, such as sprays, gas and active or passive systems, which could be used in a packaging solution. These will be discussed in the course of Task 3.

Figure 8: Mineral wool

Chapter III: Assessment of the effectiveness of the SAE AS6413 standard tests

III.1 Introduction of the SAE AS6413 standard and a brief description of the tests

The objective of the SAE AS6413 – 'Performance based package standard for lithium batteries as cargo on aircraft' standard is to develop exact performance-based packaging tests. 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 runaway of lithium batteries. The main thermal runaway hazards that are being addressed are flames, fragments, flammable vapour and surface temperatures. Potential hazards from vapour or smoke that could affect the health of passengers are not being addressed in the standard.

The SAE AS6413 standard is still under development (at the time this document was being written, November 2018) and current discussions within the SAE G27 committee will potentially lead to further changes of multiple aspects of the draft standard. Appendix B summarizes the methodology of SAE AS6413 used within this task. There is consensus amongst the SAE G27 committee members on which kind of tests methods have to be included in the standard, but different technical aspects are still being modified during each iteration of the SAE AS6413 document. The SaBatAir Consortium will take this into account and will adapt its test methods whenever the draft standard is updated.

The SAE AS6413 standard details specific test methods that have to be conducted in a specified test chamber and assess the robustness of the package when a lithium battery is set to go on thermal runaway. The different tests methods provided by the standard are summarized in Table 2.

Table 2: Type of tests that can be performed under the SAE AS6413 standard (as described in the November 2018 version)

Test name	Short description
Test I: Cells and or batteries in specific packaging	Defined as a baseline scenario, this test assesses a package that has been prepared (as is intended) by current regulation for the transport of lithium cells or batteries in air cargo.
Test II: Oversize battery in packaging	This test assesses packages that are oversized and cannot enter into the specified test chamber. The package is placed outside the test chamber but any hazards coming from it are ducted in the chamber for evaluation.
Test III: Oversize sub-system battery in packaging	This test is intended for oversized systems in large packages that could be potentially scaled down into a sub-system that is repetitive of the initial package.
Test IV: Sub-Packaging	This test assesses a sub-package that is found to be repetitive in a package.
Test V: Benign Cell@SOC	This test is intended to show if a series of cells, at a specified SOC, will not enter into thermal runaway and thus can be transported in an appropriate packaging.
Test VI: Benign Battery@SOC	This test is intended to show if a series of batteries at a specified SOC will not enter into thermal runaway and thus can be transported in appropriate packaging.
Test VII: Generic Packaging	This test is intended to assess a package that is filled with cells/batteries as intended by transport regulations with an extra margin of cells. In this way, the worst case scenario is being evaluated. If this test is successful, this package can be used to transport cells/batteries of 'similar size or smaller, same chemistry, same cell/battery manufacturer'.
Test VIII: Reduced cell configuration	This test is intended to assess a package that does not contain all cells/batteries in it. By replacing the other cells/batteries with dummy cells, this test demonstrates that these do affect the outcome of the experiment. It is possible to certify that the package is suitable for transport as intended by air transport regulations.

The SAE AS6413 standard Test I (cells and or batteries in specific packaging) is considered as the baseline and also describes the test set up and how to prepare the test article. The ambient temperature inside the test chamber, prior to testing, should be between 15°C and 30°C. The test article should be prepared a maximum of 2 hours before the initiation of the test procedure.

The standard requires the testing of cell/battery packages that are prepared for shipment as per the current dangerous goods regulations for air transportation. The cells or batteries inside the package have to be placed in such a manner that one of those cells is identified as the 'initiation cell/battery'. Around the 'initiation cell/battery' the next set of cells/batteries is called the 'propagation zone' and the set after that is the 'periphery zone. In cases of multiple layers, the cells batteries on top or bottom of the 'initiation cell/battery' are also defined as the 'periphery zone'. The 'initiation cell/battery' should be placed at the closest point to the middle of the layer next to the packaging wall. In case of multiple layers of cells/batteries in the package the 'initiation cell/battery' should be placed in the middle layer. The objective of this setup is to maximize the heat transfer from the 'initiation cell/battery' to the adjacent cells/batteries.

Prior to testing, the State of Charge of the cells/batteries has to be prepared by the Package Qualification Owner (PQO). The SAE AS6413 standard provides the possibility to perform the tests at any SOC the PQO decides. There should be a margin of 10% additional SOC. Cells/batteries that have to be transported at 90% SOC or greater should be tested fully charged at 100% SOC. To setup the SOC of the cells, two methods have been specified in the standard. The first method is to acquire, prior to testing, a look up table relating SOC and voltages of the cell/battery and determine if the Open Circuit Voltage (OCV) is at the appropriate level. The second method is through the procedures that are found in the IEC 61960-3, IEC 62133-2 and IEC 62660 standard which are based on a capacity test procedure with a specified current rate and temperature. Furthermore, witness panels can be used to check if the flames exiting out of the package can be defined as hazardous. The standard recommends to use a material like cheesecloth which is highly flammable.

The 'initiation cell/battery' should be placed in contact with an 'initiation source' covered with insulated heat material. A thermocouple should be placed at the location most representative of the cells/batteries internal temperature, which is defined for cells under 50 grams to be on the opposite side where the 'initiation source' has been placed. Additional thermocouples should be placed on each side of the package as close to the centre as possible with the thermocouple, which is on the side of the 'initiation cell/battery' and 'initiation source', to be as close as possible to these components. The external thermocouples shall remain in place for the whole duration of the test procedure. To initiate the thermal runaway, the 'initiation source' should be activated. The thermocouple which is placed on the opposite side of the 'initiation source' should be monitored and should have a rise of 5°C to 20°C per minute until the 'initiation cell/battery' reaches thermal runaway of 200°C. If the 'initiation cell/battery' has reached thermal runaway prior to reaching 200°C, remove the power of the 'initiation source'. If no thermal runaway is observed, and after reaching 200°C on the thermocouple reading, keep the temperature to that level and do not let it fall lower than 195°C. This should be performed until thermal runaway is observed or for 1 hour. The test procedure is finalised when the package shows failure or for 5 hours after the power removal on the 'initiation source'.

In the context of the SaBatAir project, 3 tests have been chosen to be assessed through the test plan of Task 2. The tests for oversized test articles (Test II and Test III) were excluded from the test plan, as a test chamber was not needed and the latter was an aspect of the test that should be evaluated. Test IV was also excluded as it is similar to the baseline test. The investigation into the parameter SOC is planned to be done with a Reduced cell configuration (Test VIII), so Test V and Test VI were excluded. The test of Generic packaging (VII) is taken into account in the test plan, as it considers worst case scenario. The Reduced cell configuration test (VIII) is included in the test plan because it requires a low amount of cells, which makes evaluating the different test set up parameters easier to test, as it generates lower exothermic energy during thermal runaway.

Test VII and Test VIII follow the baseline test scenario (Test I) with some adjustments as described in Table 3.

Table 3: Additional requirements for Test VII and VIII.

Test name	Test Procedure	Acceptance Criteria
Test VII: Generic Packaging	1) Follow the test procedure of Test I. 2) Fill the surrounding cells/batteries fully charged to assess the worst case scenario. 3) Cells/batteries adjusted to the 'initiation source' can be emptied if it is demonstrated that they would not affect the propagation of the heat.	1) All acceptance criteria of Test I should be met. 2) All periphery zone cells/batteries should not have been affected or entered into thermal runaway. If this is the case, the test can be repeated to show that the Generic Package can contain the hazards (acceptance criteria Test I) even if all the cells/batteries have been adversely affected.
Test VIII: Reduced cell configuration	1) Follow the test procedure of Test I. 2) A minimum number of cells/batteries should be placed in the package showing that the initiation cell/battery and propagation zone cells/batteries are a repetitive configuration in the package. Cells/batteries are also required to be placed in the periphery zone. 3) The empty space in the package can be replaced by dummy cells with a material which can prove that it will not affect the outcome of the test.	1) All acceptance criteria of Test I should be met. 2) The cells/batteries placed in the periphery zone should show that they have no vent opening and their voltage has remained stable at the level prior to testing.

III.2 Detailed description of the test procedure

A test chamber has been designed in accordance with the requirements of the SAE AS6413 standard draft as of November 2018, as shown in Figure 9 and Figure 10 below.

A relatively simple design for the test rig was incorporated to replicate the SAE AS6413 standard. The rig consists of an air tight chamber with a movable bottom tray that will allow for a free air space of 0.3 m^3. The sides of the chamber are made of transparent fire retardant acrylic perspex and the top and bottom are constructed out of carbon steel. The top has a 600mm x 600mm square cut out to allow for the inclusion of a pressure relief system. Cheesecloth and cotton wool was placed directly outside the packaging to be tested, which would singe or blacken if exposed to a flame. This was used as an indicator in case any substantial flames escaped the packaging.

The instruments used are described in Table 4.

Figure 9: Test chamber built in accordance with SAE AS6413 Nov 2018 draft

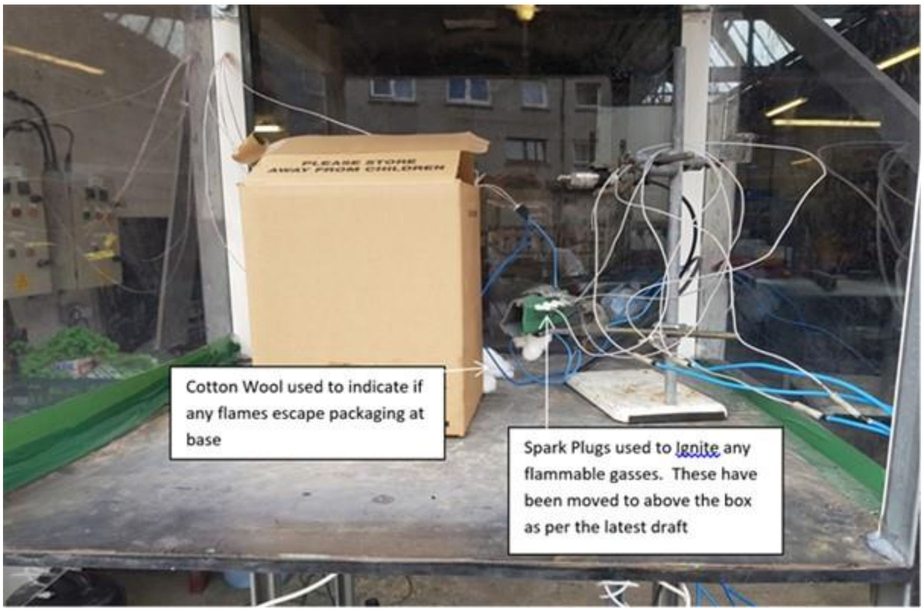

Figure 10: Setup of spark ignitors and cotton wool

Table 4: Instruments used in test chamber.

Item	**Description**	**Calibration method**
Chamber	Unistrut/Perspex design. Variable height floor to adjust air space as described in section 7 of the standard.	Chamber filled with CO_2 and verified that CO_2 level had not changed after 1 hour showing less than one air exchange.
Spark Ignitors	Motor vehicle spark ignitors x 4, sparking at 1HZ.	N/A
Pressure sensor	642R-601 programmable pressure transmitter ranging from 0 – 6 Bar.	Manufacturer calibrated with ISO17025 certificate.
Thermocouples	7 K-type thermocouples.	In house process against ISO 17025 traceable equipment @ 100°C and 200°C.
Data Logger	Squirrel SQ2020 Data logger.	N/A
Heater Cartridge	300W 10mm x 650mm heating cartridge.	As per in-house ISO 17025 certified methodology.
PIC controller	Programmable controller for heating cartridge.	N/A

III.3 SaBatAir test campaign

The purpose of the experimental tests carried out within this task is to evaluate the effectiveness of the current SAE AS6413 draft standard (see Appendix B for a summary of the methodology used) and to identify areas where further work is needed to improve the test setup and procedure definition and establish a robust standard.

The agreed initial test program is shown in Table 5. This test program is considered a tentative as it is planned to review it at key intervals following a flow chart as described in Appendix A. The test plan is therefore continuosly adapted based on the evaluation of the results obtained in the already performed test runs.The initial plan outlined in Table 5 can be divided in 6 different phases, each one with a specific objective. For example, tests planned for Phase I are dedicated to evaluate the repeatability of the 'Test VIII: Reduced cell configuration' with pouch cells, cylindrical cells and using two different SOC levels.

Table 5: Experimental test program V2.2 (December 2018). Some columns were removed to make the table readable in this word format. The full test program is in an excel format distributed with this document.

	Cell Geometry	Test type	SoC of packaged cells	SoC of initiation cell	Type of Packaging	Cell distribution	Objective of the test
Phase I	Cylindrical	Test VIII: Reduced cell configuration	30	33	no dividers	1 layer	Repeatability
	Cylindrical	Test VIII: Reduced cell configuration	100	100	no dividers	1 layer	
	Pouch	Test VIII: Reduced cell configuration	30	33	no dividers	1 layer	
	Pouch	Test VIII: Reduced cell configuration	100	100	no dividers	1 layer	
Phase II	Pouch	Test VIII: Reduced cell configuration	30	33	no dividers	1 layer	Verification of position of the thermocouples and the heater
Phase III	Cylindrical	Test VIII: Reduced cell configuration	30	33	no dividers	Multiple layers	Effect of vertical placement
	Cylindrical	Test VIII: Reduced cell configuration	30	33	no dividers - 3 boundaries	3 layers	Effect of cell to cell propagation and repeatability
Phase IV	Cylindrical	Test VIII: Reduced cell configuration	30	33	fibreboard dividers		Repeatability of the test with the use of fibreboard dividers
	Pouch	Test VIII: Reduced cell configuration	30	33	fibreboard dividers		
Phase V	Cylindrical	Test VII: Generic Packaging	100	100	fibreboard dividers	1 layer	Repeatability with generic packaging
	Pouch	Test VII: Generic Packaging	100	100	fibreboard dividers	Multiple layers	
Phase VI	Cylindrical	Test I: Cells and or batteries in specific packaging	30	33	fibreboard dividers	1 layer	Repeatability of the baseline test
	Pouch	Test I: Cells and or batteries in specific packaging	30	33	fibreboard dividers	Multiple layers	

III.3.1 Test program (December 2018)

The objective of the test program, as designed when starting the Task 2 testing campaign, is to verify a number of parameters of the current SAE AS6413 draft standard.

The Task 2 testing is intended to achieve the following:

1. Assessment of the tests repeatability and reproducibility
2. If the tests repeatability and/or reproducibility are not reached, investigate and suggest possible test improvements or modifications.
3. Generate experimental data to allow the validation of the thermal model.

The parameters to be investigated include the effect of separator materials, the effect of thermocouple placement and the effect of increasing SOC above the currently allowed maximum for air transport of 30%.

III.3.1.1 Phase I tests

The first four lines of the test program (Phase I as described in Table 5) are designed to verify the repeatability and consistency of the thermal runaway event produced when performing Test VIII: Reduced cell configuration. This parameter has been identified as critical to assess the tests of the standard, as it will ensure that a consistent result can be obtained when the same test is done by different testing laboratories.

III.3.1.2 Exact test setup

The test will be set up closely following the requirements of the Reduced Cell Configuration test (Test VIII) (see details in section III.1 of this document). Figure 11 below shows the cell layout, of four batteries placed on the edge of the package, surrounded by 'dummy' cells of the same size-18650 type cells. These dummy cells are manufactured out of solid aluminum (standard grade).

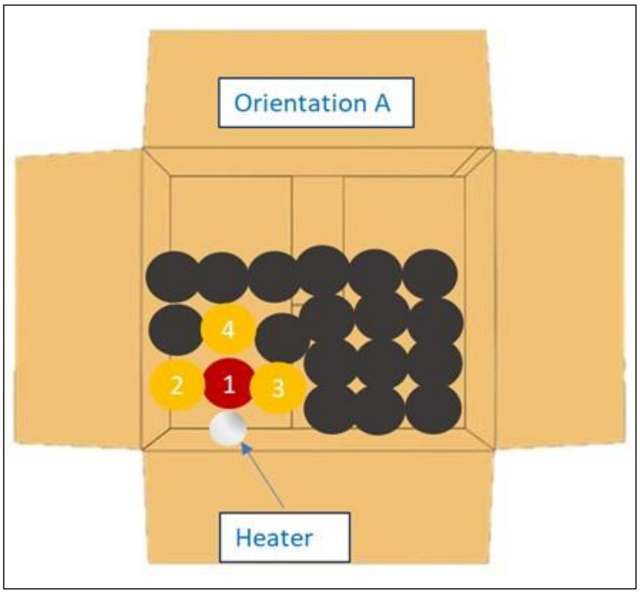

Figure 11: Cell layout and position of the heater as prepared for Phase I tests

Thermocouples positions for both cylindrical cells type 18650 (Phase I tests) and pouch cells (Phase I tests) are shown in Figure 12 below. It should be noted that these positions are located differently from what is described in the current draft standard, which requires only one thermal couple inside the box. This has been changed in order to allow the collection of extra temperature measurements at different positions, to allow verification of how the thermal runaway propagates through the cells. The temperature on the outside of the box was not measured here as the objective of this Phase I test is to evaluate the repeatability of the test and not to evaluate the resistance of the package to thermal runaway.

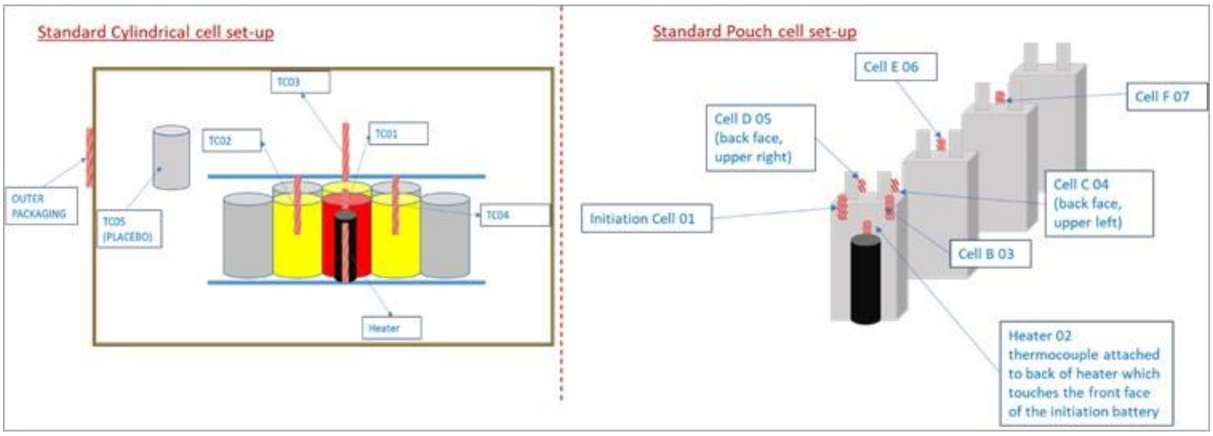

Figure 12: Position of the thermocouples as described in the SAE AS6413 draft standard (version of November 2018)

The heater cartridge used is shown in Figure 13 The heater, 8mm thick and 40mm long, is capable of reaching temperatures in excess of 750°C and is rated at 200W running at 230V. This is wired to a PID (A proportional–integral–derivative controller) which is a control loop feedback mechanism widely used in industrial control systems, a variety of other applications requiring continuously modulated control which regulates the heater temperature based on the thermal response of a thermocouple.

Figure 13: Example of heater cartridge used in Phase I tests

In order to comply with the SAE AS6413 draft standard, thermocouple TC03 (placed between the initiation cell and a periphery cell on the far side from the heater cartridge) is classed as the control thermocouple, which would control the heater cartridge to raise TC03 by between 5°C and 20°C a minute.

III.3.2 Test parameters

Table 6 shows the parameters which have been kept constant during the initial tests.

Table 6: Test parameters

Parameter	Setting
Chemistry	NMC
Capacity	3.2Ah
Test configuration	Adjusted Test VIII: Reduced Cell configuration
State of charge (SOC)	30% or 100% (based on recorded voltages)
Dividers	No dividers: cells and dummy cells touching (where possible)
Layers	One layer
# of cells	4
Repeats	3

III.3.3 Recorded parameters

Table 7 shows the parameters recorded before and after testing.

Table 7: Recorded parameters

Parameter	Objective
Cell voltage before test	Verification of SOC.
Cell voltage after test	Verification that thermal runaway occurred.
Temperatures	All temperatures read from the thermocouples were logged with one reading every 1 second. Readings were discontinued once temperatures on the initiation cell and periphery cells had returned to ambient. The current test draft requires to monitor the temperature around the package for a period of 5 hours following thermal runaway. The packaging performance was not the purpose of this test phase therefore, this requirement was not followed.
Pressure	To provide a rough calculation of gas produced.
Maximum temperature	Maximum temperature reached for each thermocouple to understand severity of thermal runaway.
Flame	A visual determination of whether a flame was produced in consequence of the thermal runaway.
Debris	A visual determination of whether debris was ejected from the box.

Chapter IV: Thermal modelling

IV.1 Introduction

Heat propagation simulation over an array of Li-Ion cells, within a transportation package, has been performed to get better insight into transient heat flow across the package. The assumption is that one of the cells in a package accidentally goes into thermal runaway either by being mechanically penetrated with a sharp pointy object, which causes internal short circuiting, or by being thermally abused with an external heat source. In either case, this mechanical or heat forcing triggers a chain of electro-chemical exothermic reactions and a rapid heat release occurs accompanied with high temperatures of the cell. This in turn may or may not, depending on the SOC of the batteries, (which directly influences the amount of heat it will release if in thermal runaway) trigger other cells in the immediate vicinity. The most detrimental situation is when the whole cell package burns out due to a thermal runaway cascade effect. The cascade effect refers to the event when all the cells in a package go into thermal runaway one after the other with a certain (not necessarily regular) time period in between. Although the SOC is likely to be the most influential parameter in the heat release intensity during the thermal runaway, it is also important to take into account the way cells are stacked in a package, staggered apart or not, and in case they are apart, which material in between the cells may be a good insulator to prevent thermal runaway (TR) cascading effect. All these questions may be tackled by a numerical simulation along with some necessary inputs from thermal or mechanical cell abuse experiments.

IV.2 Objectives

The objectives of the thermal modeling activity within this study are:

1. To assist experimental testing by defining the optimum parameters and testing conditions through simulating different testing scenarios. For example, to determine the best position of the control thermocouple, the heat generated by the initiation source was mapped during its propagation through the cell.
2. To complement experimental testing and to decrease the number and cost of the tests. Most of the experimental tests planned in this study are done according to the reduced cell configuration (Test VIII of the SAE AS6413 standard) as it requires a fewer amount of cells. To get an idea on how the thermal runaway propagates inside a package filled with cells, (Test I or Test VII of the SAE AS6413 standard) a simulation is done with the results of the experimental data obtained on reduced cell configuration.
3. Gain a better understanding of the thermal runaway propagation inside a package filled with lithium cells

IV.3 Cell pack geometry (CAD) model

A CAD model is designed based on a few requirements. It has to contain enough cells to properly observe thermal runaway propagation in a package, and to be flexible in terms of adding or removing dividing walls in between the cells and fluid/insulator regions in the package. The software Ansys Fluent v19.2 is used to model heat generation and propagation across the cell package. It is assumed that thermal conduction is the only mechanism by which heat propagates through the package. Since the air space in between the cells is rather small, in case of tightly packed cylindrical cells, and the box containing the cells is closed, it is assumed that heat propagates through the air region only by conduction as well. In other words, air is taken to behave like a solid with its own thermophysical properties. Figure 14 shows a schematic of a geometrical model for a 5x5 cell package. The box around the cells (red line on the picture), and dividers (blue line on the picture), are not included in the CAD model with their real thickness. They are designed as zero-thickness plane surfaces in the CAD model. However, in the Fluent solver they are virtually given a finite thickness. This offers greater flexibility, since it is not necessary to make a new model and a computational mesh each time the thickness of the dividers or the box around the cells is slightly modified.

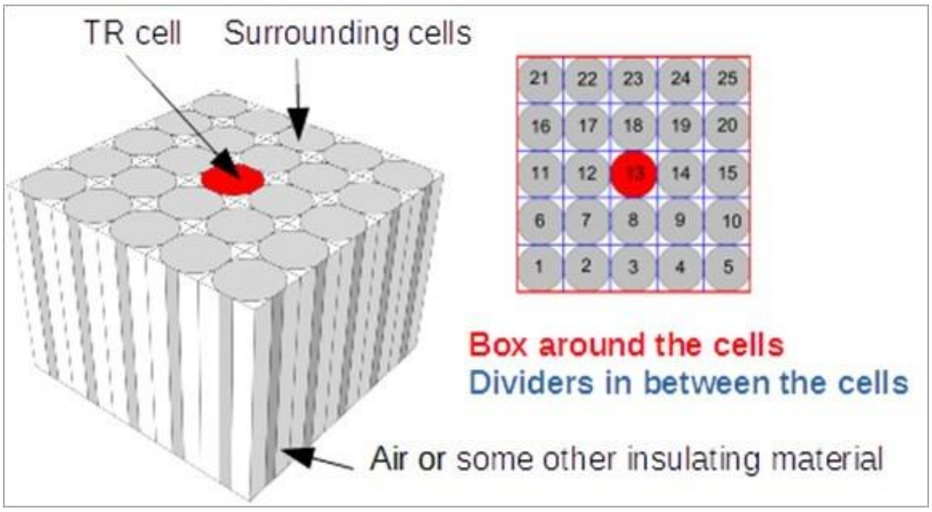

Figure 14: Geometrical model for a 5x5 cell package

IV.4 Computational mesh

Ansys' Fluent is a finite volume based on general thermo-fluids solver and, as a first step, a finite volume good quality computational mesh must be generated. For this purpose, the Ansys Workbench package is used as a pre-processor since it can generate high quality meshes which are dominated by extrusions. If a surface mesh is defined on one side of the domain, it can be easily extruded to the other side with a specified pitch. Moreover, the Ansys Workbench Mesher is capable of automatic naming of the interior mesh surfaces which exist in between the cells as well as in between fluid region. This provides a greater flexibility while using these interior faces later on in the Fluent solver to place dividers of a certain virtual thickness and certain properties to examine insulation effects of the dividers. It is also worth clarifying, as already mentioned above, that the box around the cells as well as dividers are not actually meshed, they do not contain computational cell volumes. They are very thin regions and for that reason a special feature of Fluent is used where one can impose virtual thickness through which heat conduction can be modelled only in a surface normal direction. Taking into account a very small thickness of these regions, this should be a fair approximation. An example of a computational mesh is given on Figure 15 for a 5x5 cell package.

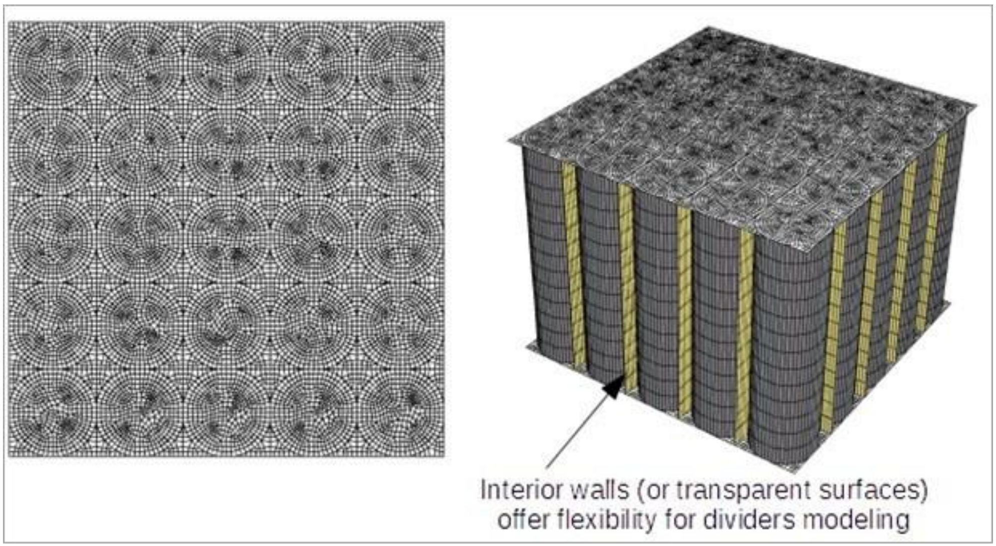

Figure 15: Computational mesh for a 5x5 cell package

IV.5 Model setup

A black-box approach is utilized for the modelling of heat propagation across the cell package and in that case Fluent solves only one equation which defines heat propagation within the solid region:

$$\frac{\partial}{\partial t}(\rho h) = \nabla \cdot (k \nabla T) + S_h$$

Where:

ρ = density
h = sensible enthalpy
k = conductivity
T = temperature
S_h = volumetric heat source

A 'Black-box model' actually means that, rather than describing the mechanisms leading to the heat generation in the battery, the heat generation is modelled directly. A volumetric heat source of a certain strength is imposed inside the cell volume which should result in temperatures being observed in the experiments. Therefore, solving all the equations which describe thermo-chemical and electro-chemical processes within a cell is avoided. Each cell is considered to be a made up of a homogeneous material with its own thermo-mechanical properties which should in case of a thermal runaway, release a certain amount of heat. The strength of the heat source is estimated from the experimental temperature recordings. The computational model is transient which provides the time evolution of temperatures across the cells and the possibility to introduce cascading effect.

The model uses User Defined Functions (UDF) to describe the specific behaviour. These functions are pieces of C-code run by the solver, allowed to make additional calculations and to change boundary conditions during the simulation. A first UDF contains the heat source definition, describing the black box thermal behaviour of the batteries. Other routines are run after each time-step of the simulation to track down maximum and average temperature of each cell, which are necessary to trigger the heat release.

A schematic in Figure 16 outlines how the temperature evolution during the experimental thermal runaway tests is used to define two heat sources as a function of time. These heat sources are constant during a certain period of time, and approximate the power necessary to reproduce a certain temperature increase, as observed in experiments. A first smaller heat source is imposed during the time delay between reaching the venting temperature T_1 and the onset of fast thermal runaway T_2. During a short time interval, a larger heat source is imposed, corresponding to the heat released during the fast thermal runaway stage (reaching T_3).

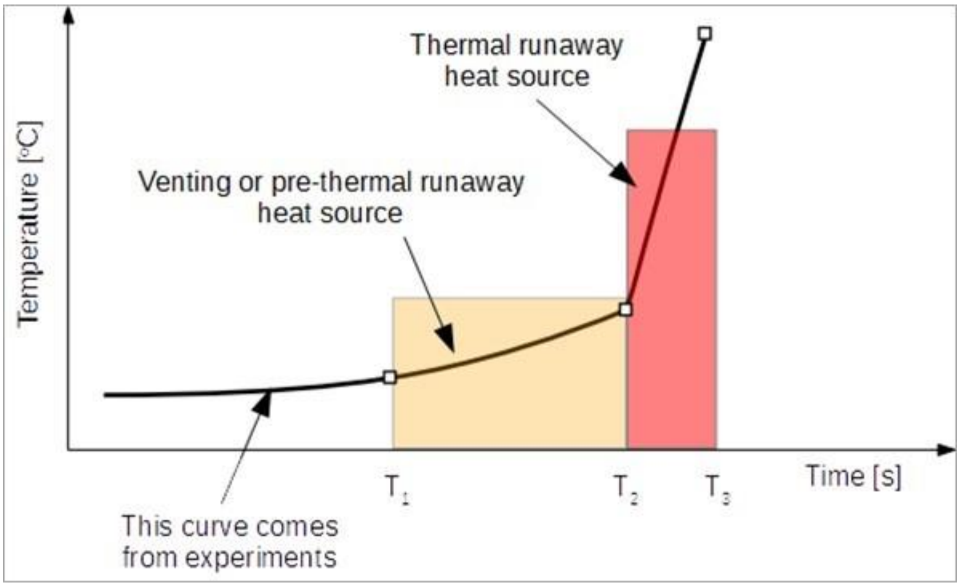

Figure 16: Heat source definition for the black-box modeling approach

Since only the energy equation is solved during the simulation, boundary conditions require the temperature to be defined at the faces of the box. Convective boundary conditions are chosen as the most suitable, meaning that the convective heat co-efficient along with the free-stream temperature on the outside of the box must be defined. The simulation starts from an initial condition which may either be an environmental uniform temperature over the whole domain and possibly a temperature T_2 which is imposed within the cell which goes into thermal runaway.

The thermal modelling will be done according to the following plan (updated after first simulations and experimental results) and summarized in Table 8:

1. The initiation cell is located at the edge of the box (middle of the row).
2. The cells will be simulated at a 30% SOC and 100% SOC.
3. Cylindrical and prismatic (pouch) cell geometries swill be considered.

4. Four main chemistries will be simulated (based on literature data): NMC; NCA, LFP and Li metal if data available.
5. Two different cell stacking will be considered: 1 layer and 3 layers of vertically stacked cells.
6. Dividers inside the box will be considered: cardboard, vermiculite and sand.

This plan might be updated based on experimental results and special needs.

Table 8: Summary of the thermal modelling activity

Position of the initiation cell	At the edge and middle of the row
Positions of the cells	1 layer 3 layers stacked vertically
SOC of the cells	High SOC : 100% Low SOC : 30%
Cell chemistry	NMC NCA LFP Li metal if data available
Cell geometry	Cylindrical Pouch
Packaging dividers	Cardboard Vermiculite Sand

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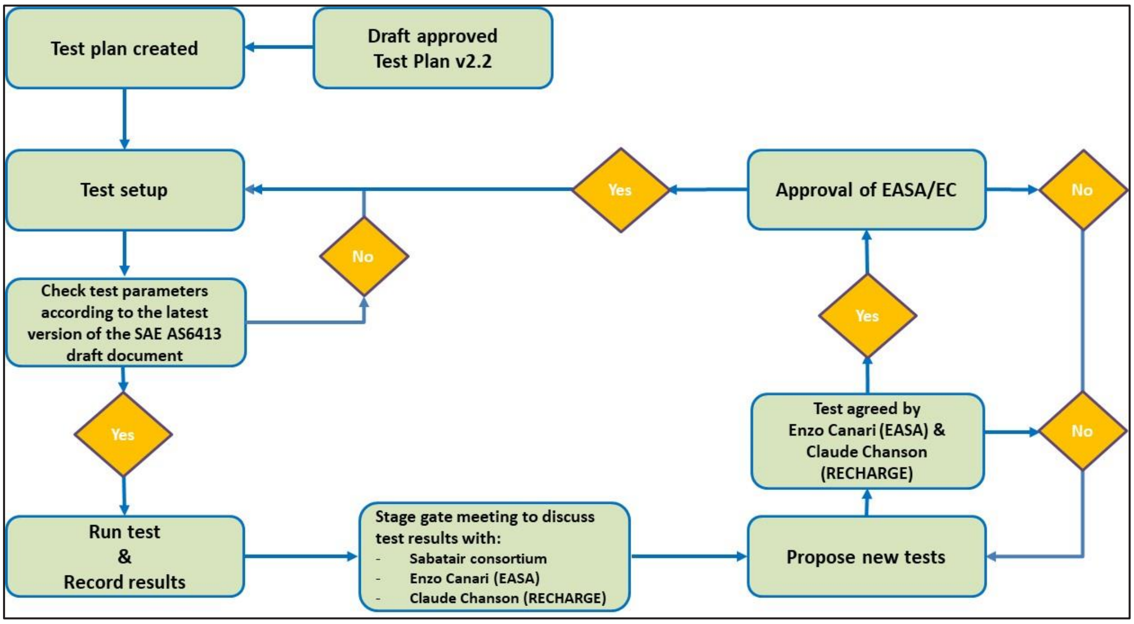
Appendix A

Decision flow for changes to the test program



Appendix B

Test parameters as per SAE AS6413 Nov 6th Draft

The testing was setup in accordance with the November 6th Draft of SAE AS6413. The majority of Task 2 testing was carried out using the Reduced Cell Configuration test (Test VIII), which, according to the November 6th draft (2018) was to be carried out using the procedure in 5.1.2 (SAE AS6413 5.8.2).

Section 5 requires the test house to follow the requirements of section 6.1 (Test apparatus and equipment), and this equipment is detailed in section III.2.

1. Preparing Batteries inside Packaging

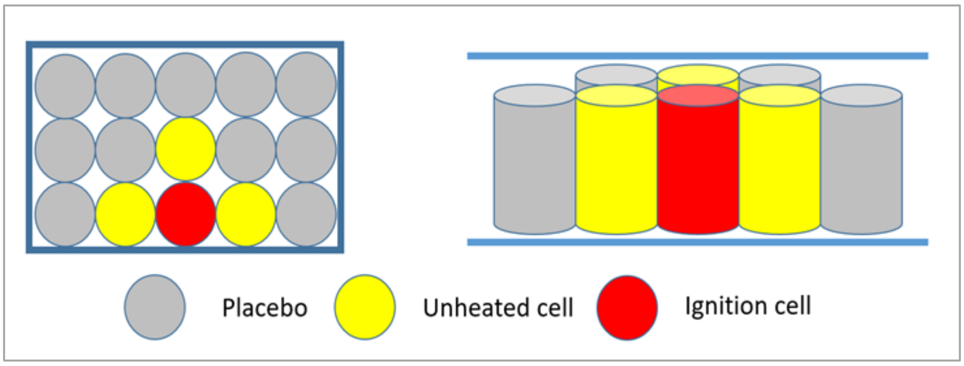
a. Battery and Thermocouple Arrangement

The ignition and periphery cells were arranged inside the package with thermocouples attached.

According to the SAE AS6413 November 2018 version only the ignition cell temperature to be monitored, however to aid the evaluation of the test protocol, extra thermocouples were placed on all cells, as well as on the placebo cells. These are described as in table B.1 and showed in Figure B.1.

Table B.1: Position of thermocouples in test setup

Thermocouple ID	Where to attach
Heater	Attached to Heater band
TC01	Attached to ignition Cell
TC02	Neighboring Cell (Unheated)
TC03	Neighboring Cell (Unheated)
TC04	Neighboring Cell (Unheated)
TC05	Furthest away placebo cell
Outside Packaging	Outer surface of packaging closest to ignition cell



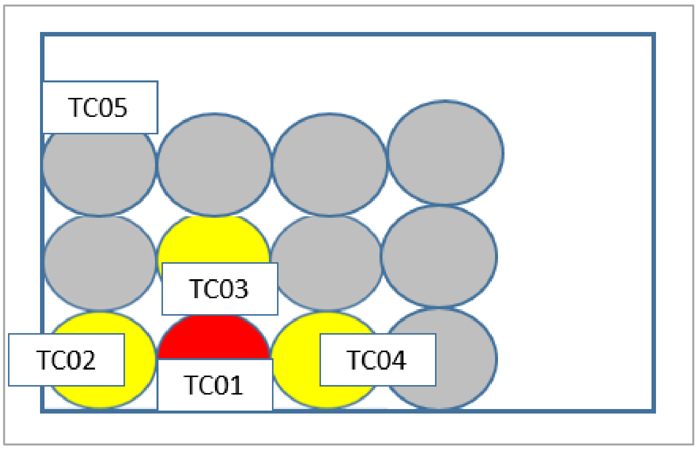


Figure B.1: Thermocouple map

Once the batteries had been arranged and prepared in accordance with the test plan, the box was sealed using the tape prescribed by the box manufacturer.

b. Preparing the inside of the chamber before sealing

The test chamber is prepared in accordance with SAE AS6413 5.1.2 (version of November 2018);

- Ensure that all 4 spark plugs are operating correctly. The spark plugs are to be positioned above the box, an equal distance between the top of the chamber and the top of the box.
- Ensure that the thermocouple named 'Outside Packaging' is taped to the outside of the package nearest to the heated cell.
- A piece of cheesecloth should be placed on the outside of the packaging nearest to the side where the ignition cell is placed.
- Ensure the Perspex on the chamber wall is clean from the inside so that the test can be clearly viewed from the outside. Use white spirit if necessary.
- Ensure the chamber fan is turned on and functioning.
- Verify that the pressure relief value is closed, and functioning.

2. Test Procedure (VIII – reduced cell configuration)

The testing is then carried out using the following procedure:

- The data-logger is set to record, and power is supplied to the heater band and spark plugs. The heater is programmed via the PID controller to produce a heating rate of between 5°C – 20°C/min (measured at the back side of the ignition cell – TC03) (5.1.2 g)
- The temperature should be allowed to increase until TC03 reaches 200°C. Once this is reached, the temperature should be kept steady at 200°C until thermal runaway is achieved, or 1 hour – whichever occurs first. (5.1.2 J) Once this condition has been met, the power is removed from the heater band.
- The box under test is to be monitored (using external camera) until either a failure occurs, or 5 hour after the removal of the heat source (5.1.2 k)
- The test operator should make notes of any flames, or debris originating from inside the test box. This can be monitored visually, as well as by examining the cheesecloth following the test.

3. Reporting

A test box is considered to meet the requirements of SAE AS6413 if, following testing;

- No ignition, flames or debris were observed exiting the packaging
- The gas collected in the chamber did not ignite
- No chamber safety devices were activated (for example, the pressure relief valve)
- From the time the initiation cell enters thermal runaway, the temperature of the external surface does not exceed 150°C for more than 3 minutes, or, the average temperature observed does not exceed 100C during the remaining 5 hours following removal of the heat source (5.1.3 e)
- No physical damage to the packaging should be visible and all packaging contents should have been contained.