SABATAIR
Task4:
Lithium ion cell exposure to an on-board external fire: Test Program

Task	**4**	Characterisation of on-board fire-protection facilities; assessment of their contribution to the effectiveness of the proposed packaging solutions

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Summary

This document describes the test program for the full-scale Lithium battery external fire tests which took place in the context of Task 4 of the Sabatair research project, which is funded by the European Commission DG MOVE.
Two main conclusions are derived from the test results:

- The Aircraft built-in fire suppression system inhibits propagation of thermal runaways for the tested cell configuration and SoC conditions
- For the tested scenario, a Fire Containment Cover provides appreciable protection against the threats of an external fire event.

One of the objectives of the Sabatair project is to identify mitigating measures that could be put in place to ensure that the severity of lithium battery fire could be reduced to a level that could be within the capability of the aircraft's onboard fire suppression system. This involves the evaluation of the following battery fire scenarios:

- a thermal runaway initiated from inside this package (**internal** fire)
- a lithium battery fire which does not originate but eventually involves transported cells/batteries (**external** fire)

I. Introduction

One of the objectives of the Sabatair project is to identify mitigating measures that could be put in place to ensure that the severity of lithium battery fire could be reduced to a level that could be within the capability of the aircraft's onboard fire suppression system. This involves the evaluation of the following battery fire scenarios:

- a thermal runaway initiated from inside this package (**internal** fire)
- a lithium battery fire which does not originate but eventually involves transported cells/batteries (**external** fire)

The objective of Task 4 of the Sabatair project is to study the external fire threat considering different level of protection for the packaging of lithium batteries at different state of change, taking also into account the expected typical performance of cargo compartment fire protection systems installed on large aeroplanes.
The detailed description of the test plan is included in deliverable D4a.
The tests were performed in an 1:1 aircraft cargo compartment mock-up made of steel with an operable aircraft fire suppression system. In a 3-step approach, the external fire scenario was assessed:

- Without the aircraft fire protection system operating
- With the aircraft fire protection system operating
- With the aircraft fire protection system operating and a fire containment cover (FCC) for additional fire protection

I.1. Aircraft Fire Protection: Detection and Suppression

Fire detection systems are designed to alert flight crew on the cockpit within 1 minute of a fire starting. Based on the information provided by the detection warnings, flight crew initiate the suppression of any fire by discharge of Halon gas into the affected cargo compartments.
Halon is a very effective suppression agent which operates by chemically reacting with the radicals generated by a fire, to inhibit the reaction. To achieve the extinguishing effect, sufficient Halon needs to be released to achieve a volumetric concentration of 5% of the compartment air as a first shot, for a fire knock-down effect. Following this, a concentration of 3% must be continuously maintained for the rest of flight.
With this approach, lower deck cargo compartment fires can be suppressed for up to 360 minutes on wide-body aircraft. Nevertheless, maintaining the concentration of Halon is crucial to the effectiveness of the system, and therefore it is essential that the cargo compartment remains air-tight
The phenomenon of thermal runaway of lithium batteries in an aircraft environment can be catastrophic [1]. At the least it can range from limited degradation of personal equipment, or minor damage to the overhead storage compartment. In the case worst situation, thermal runaway in high density package of Lithium batteries can result - and has been implicated - in hull losses.
FAA tests show that even a small number of overheating batteries emit gases that can cause explosions and fires that cannot be prevented by traditional fire suppression systems. In view of the possible consequences, Lithium batteries are classified as hazardous materials, therefore particular care and consideration must be taken to ensure safe operations in relation to use and transport of Lithium batteries (or devices containing Lithium batteries) when in an aircraft environment.

II. Test Chamber

II.1. Test Chamber Layout

All tests were carried out in a mock-up of a wide-body lower deck cargo hold (see Figure 1 for more details on the dimensions). The cross section of the test rig was comparable to the cross section of a lower deck cargo hold of an A330 family aircraft. The length was reduced to 8.4m to meet the requirements of the Minimum Performance Standard for Aircraft Cargo Compartment Halon Replacement Fire Suppression Systems [2]. The total volume of the test compartment was 56.6m^3.

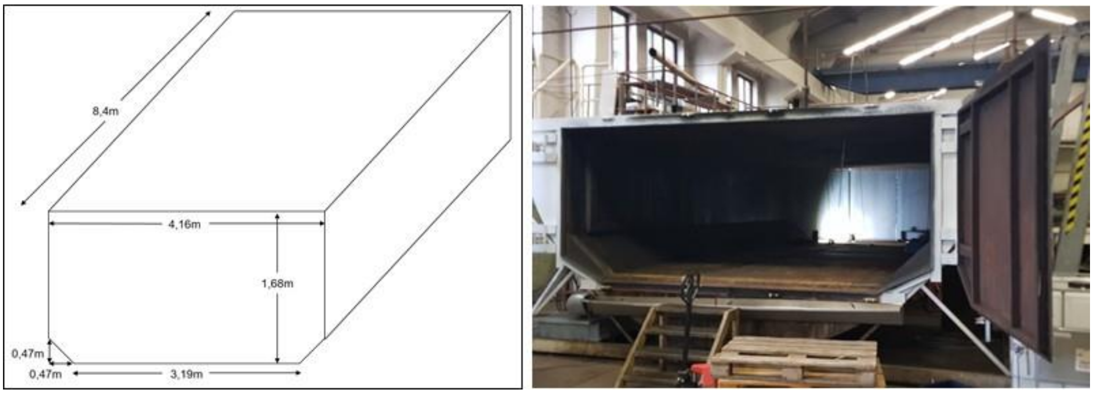


Figure 1: On the left a sketch of the fire test chamber and on the right a photograph of the fire test chamber

The inner structure (compartment walls and floor) were made from mild steel sheeting in order to preserve the article for multiple testing.
The compartment was equipped with multiple sensors to record temperature, oxygen concentrations, and pressure.
The compartment was configured to have a leakage rate representative for an in-flight leakage rate of an average Airbus aircraft.
The leakage from the compartment was configured to simulate the U-shape of the cargo door seals that are on a real aircraft. Perforated ducts were installed inside the compartment in the shape of the perimeter of a cargo door. The ducts were vented to the outside of the test article using a single connection to the constant speed pump (see Figure 2).
A constant speed pump was installed in the exit of the duct for drawing air out of the compartment to simulate an in-flight leakage rate.

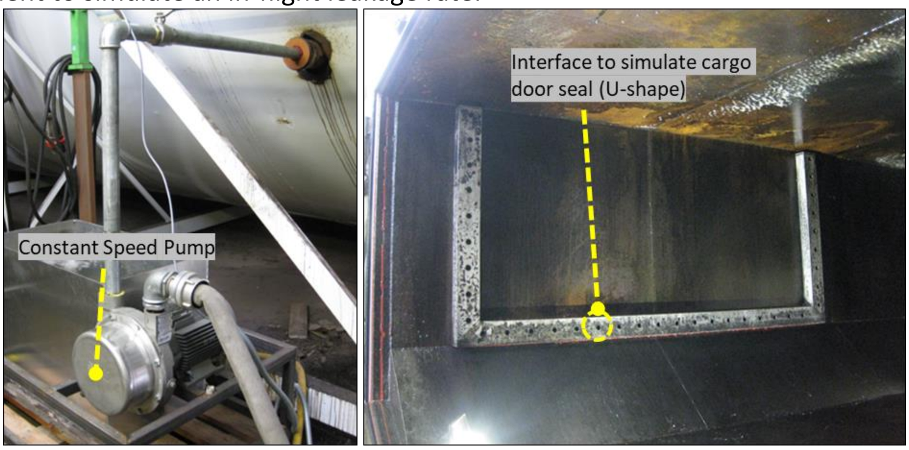
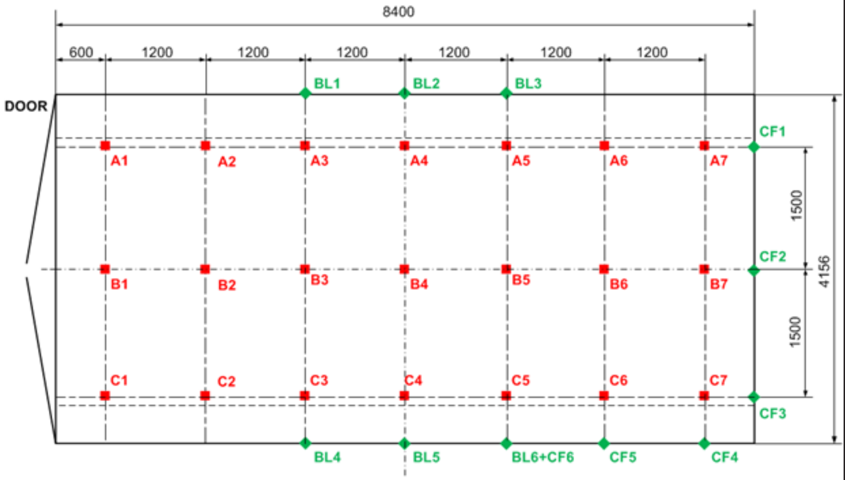


Figure 2. In-flight Leakage Simulation

The test article was outfitted with a pressure equalization valve that is used onboard Airbus aircraft to compensate pressure differentials between the cargo hold and adjacent areas. The valve was installed in the end wall of the test compartment. This installation position is representative to the installation position of the valve onboard Airbus aircraft.

II.2. Test Chamber Temperature measurement instrumentation

Temperature measurements were taken throughout the compartment at ceiling and sidewall level. Temperature sensors type K thermocouples (NiCr-Ni) were used. Figure 3 shows a top view of the test compartment and illustrates the position of the thermocouples on the ceiling and on the sidewall.



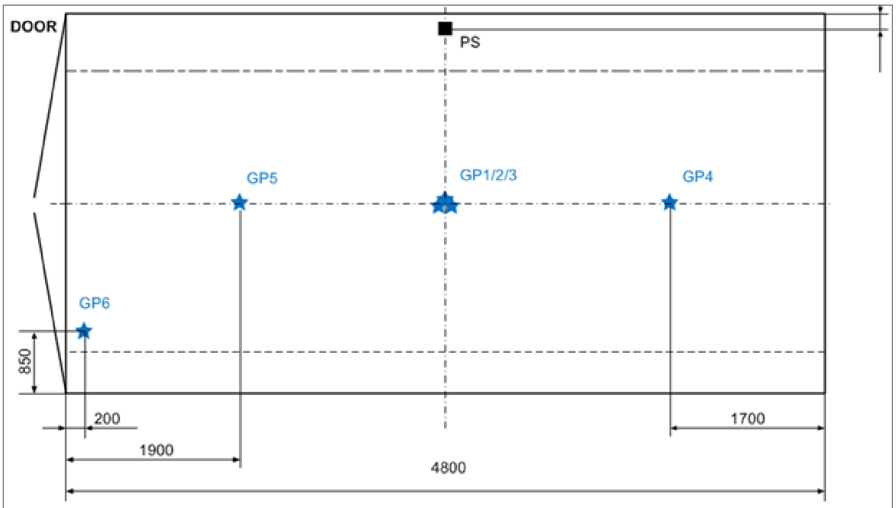
Thermocouple		Position and Configuration
■	A1 – A7 B1 – B7 C1 – C7	Ceiling thermocouples - 25mm below compartment ceiling
◆	BL1 – BL6	Sidewall thermocouples for Bulk-Load Fire Configuration; 305mm below ceiling – 25mm from sidewalls
◆	CF1 – CF6	Sidewall thermocouples for Containerized Fire Configuration; 305mm below ceiling – 25mm from sidewalls

Figure 3. Thermocouple Position

II.3. Test Chamber Oxygen Concentration and Pressure Measurement instrumentation

Oxygen volumetric concentrations were measured inside the cargo compartment at six different locations during test execution. The oxygen analyzers used paramagnetic oxygen analysis technique to measure the oxygen concentration.

A pressure transducer was installed to monitor the overpressure mainly during the early phases of the test. The pressure transducer had a pressure range from 0 to 20 hPa. Figure 4 shows a top view of the test compartment and gives the position for the oxygen sample probes and the pressure transducer.



Probe N°	Position
GP1 – Gas Sample Point 1	Center line – 50mm below compartment ceiling
GP2– Gas Sample Point 2	Center line – 600mm below compartment ceiling
GP3– Gas Sample Point 3	Center line – 200mm above compartment floor
GP4– Gas Sample Point 4	Center line – 150mm below compartment ceiling
GP5 – Gas Sample Point 5	Center line – 150mm below compartment ceiling
GP6 – Gas Sample Point 6	200mm above compartment floor
PS – Pressure Sensor	Pressure Sensor – 25mm below compartment ceiling

Figure 4. Position of Pressure Sensor and Gas Sample Points

II.4. Test Chamber Halon Concentration Measurement instrumentation

12 Halon Sensors were evenly distributed within the test chamber. Halon measurement was based on NDIR (Non-Dispersive Infrared) spectroscopy.
The Halon sensors were located in a setup comparable to the sensor location typically used for aircraft flight testing (see Figure 5). 8 Sensors were located 20 cm below the ceiling in order to estimate the distribution on this level. Additionally, 20 cm distance from the sidewalls was kept. 4 Halon Sensors were located 20 cm above the floor. The sensor calibration was executed according to the specification of the Halon sensor manufacturer.

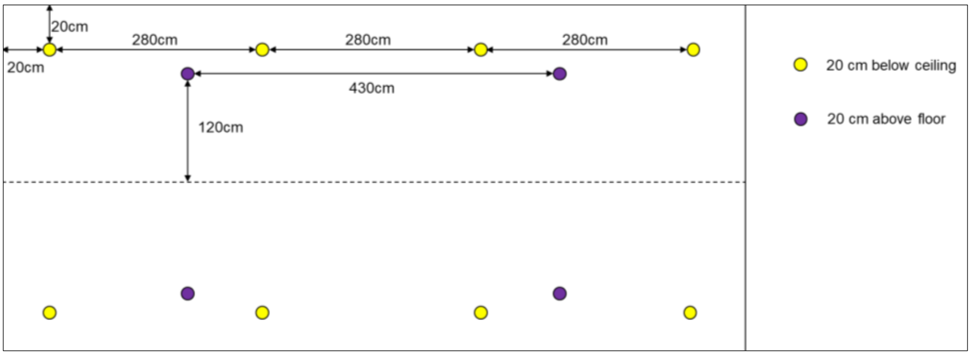


Figure 5: Halon Sensor location

II.5. Test Chamber Fire suppression system

The test chamber was equipped with a Halon 1301 fire suppression system representative of the aircraft system architecture. The fire suppression system comprised a high-rated discharge container and a flow-metered container (see Figure 6). The fire suppression system delivered a halon mass equal to a commercial aircraft of comparable cargo compartment volume.
For the test, the fire suppression system was triggered manually. The weight of Halon Bottle 1 and Halon Bottle 2 was continuously monitored during the tests.

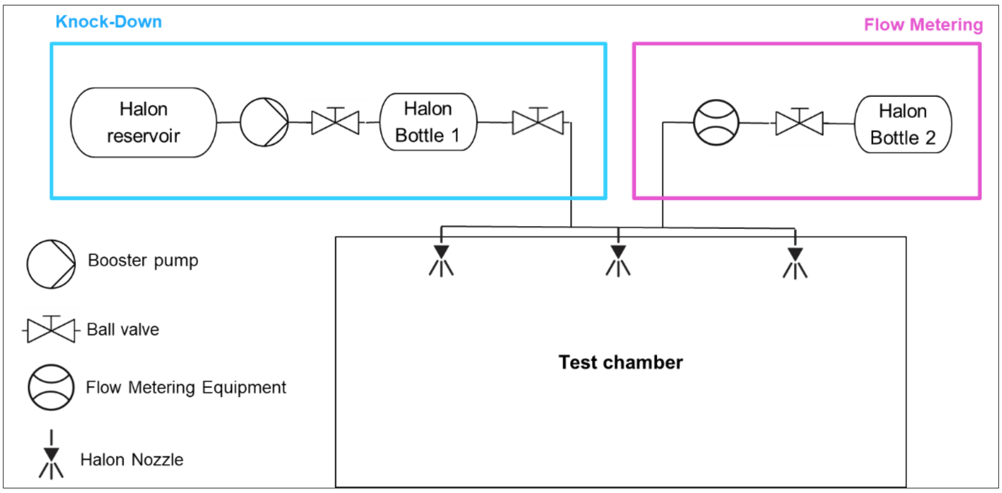


Figure 6: Schematic of the Halon Discharge system of the test chamber

II.6. Discharge Nozzles

Three standard Halon discharge nozzles were installed in the compartment ceiling. Figure 7 provides a top view of the test compartment and gives the position of the discharge nozzles. The nozzles were accommodated in cavities ensuring that the nozzles did not protrude into the test compartment. The discharge nozzles were not evenly distributed in the compartment ceiling as the construction of the test article did not allow an even spacing of the nozzles.

Figure 7 also shows the location of the pressure equalization valve and the location of the vent port for the in-flight leakage simulation.

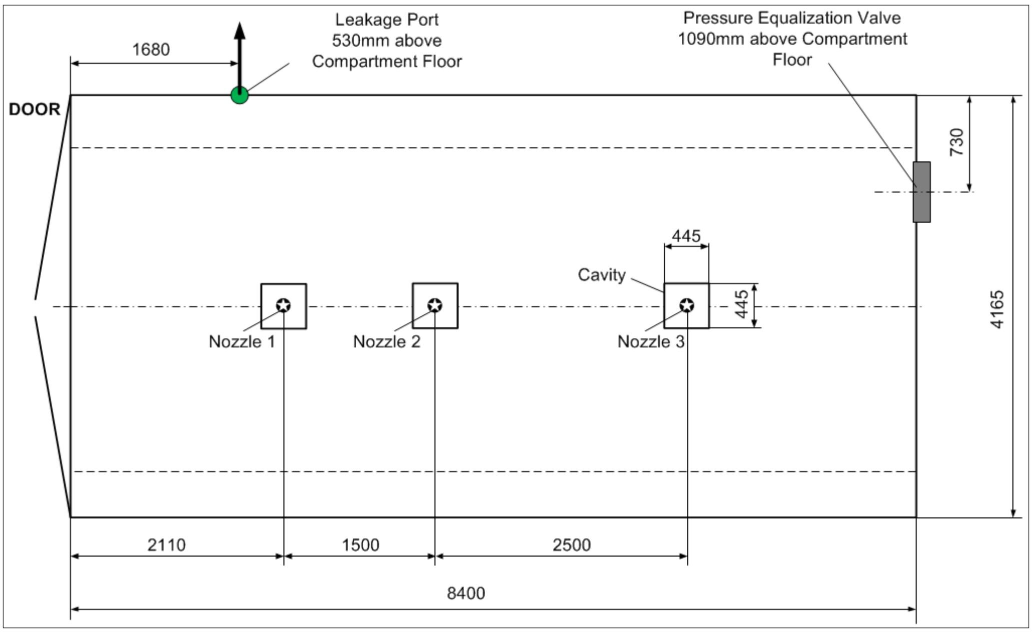


Figure 7: Position of Discharge Nozzles, Leakage Port, and Pressure Equalization Valve

II.7. Test Chamber video instrumentation

Two video cameras were located in the compartment in a way that an optimum view to the ignition box and the cells boxes was provided (see Figure 8: Video Camera instrumentation including field of viewFigure 8).

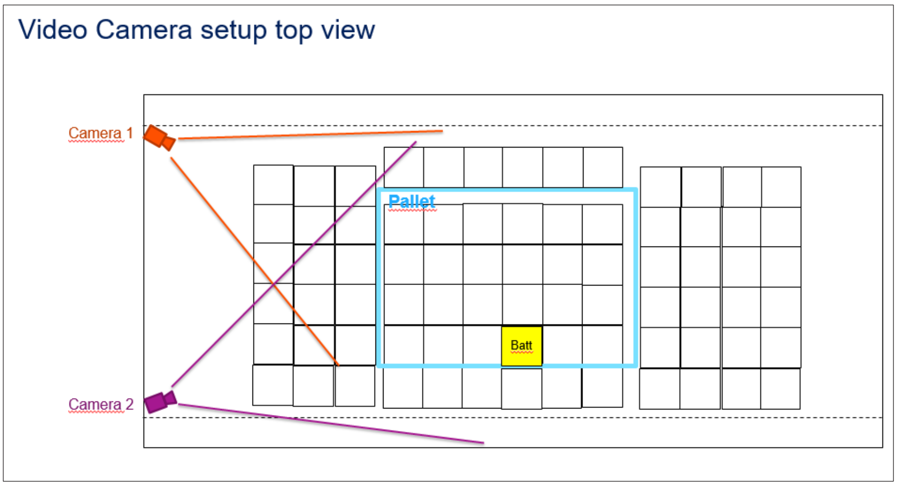


Figure 8: Video Camera instrumentation including field of view

III. Fire load

III.1. Cardboard boxes

The fire load for this scenario consists of single-wall corrugated cardboard boxes, with nominal dimensions of 45.7 by 45.7 by 45.7 cm. The weight per unit area of the cardboard is 0.5417 kg/m^2. The boxes are filled with 1.1 kg of loosely packed standard weight office paper shredded into strips (not confetti), see Figure 9. The final weight of the box and shredded paper is 2.0 ±0.2 kg. The boxes are conditioned to room standard conditions. The flaps of the boxes are tucked under each other without using staples or tape.

Figure 9: Cardboard Box filled with shredded paper

III.2. Ignition process

An ignition box shall be prepared as shown in Figure 10, refer also to [2].

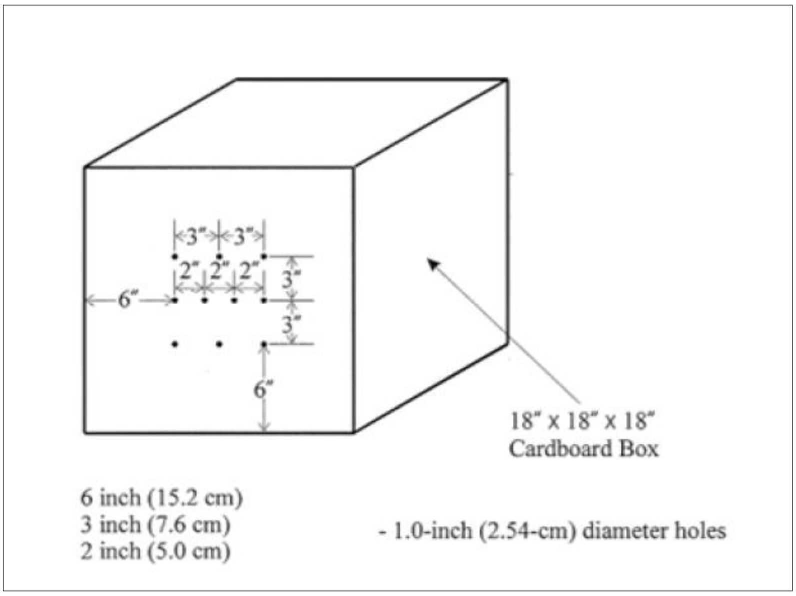


Figure 10: Ignition Box

The fire inside the ignition box is started by applying 115 volts alternating current (VAC) to a 2.1m length of nichrome wire. The wire is wrapped around four folded (in half) paper towels. The resistance of the nichrome igniter coil is approximately 7 ohms. The igniter is placed into the

center of a box on the bottom outside row of the stacked boxes. Several ventilation holes are placed in the side of the box to ensure that the fire does not self-extinguish.
The configuration of the cardboard boxes and the position of the ignition box shall be adopted to the needs of this test.

III.3. Cardboard Box arrangement

The boxes are stacked in two layers in the cargo compartment in a quantity representing 30% of the cargo compartment empty volume. For a 56.6m^3 compartment, this requires 178 boxes (see Figure 11). The boxes touch each other to prevent any significant air gaps between them.

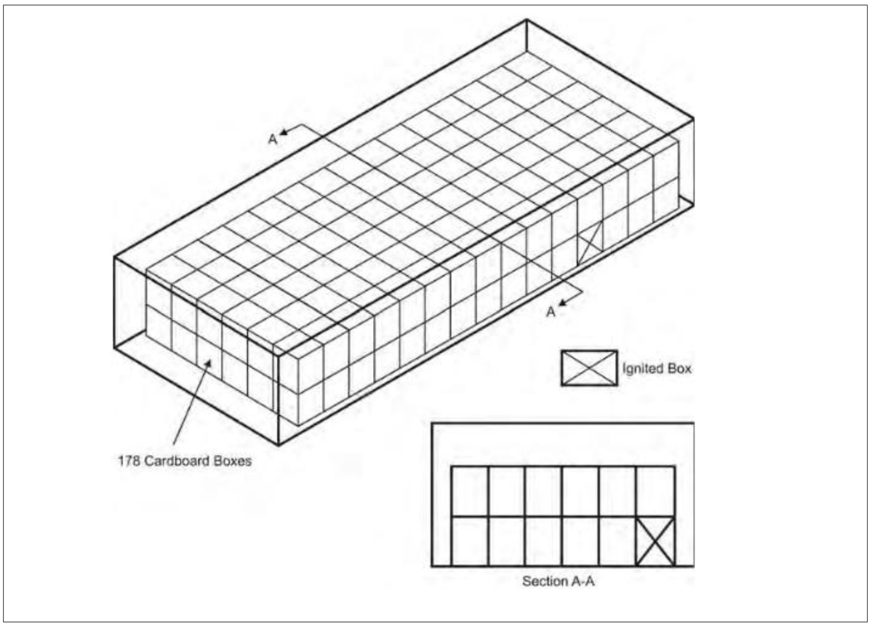


Figure 11: Arrangement of Cardboard Boxes as fire load for the Bulk load fire test of the Minimum Performance Standard for Aircraft Cargo Compartment Halon Replacement Fire Suppression Systems [2]

IV. Test specimen

IV.1. Lithium ion cells

The cells to be tested are standard 18650 Lithium Ion rechargeable batteries. More details related to the cell selection are available in the deliverable D2a.

Two different cell brands (Manufacturer 1 and Manufacturer 2) have been selected to represent a random mix. The cells underwent successfully the UN38.3 tests. The technical specification of the batteries are as follows:

Brand	Manufacturer 1	Manufacturer 2
Nominal Capacity	3500mAh	3500mAh
Chemistry	$LiNiCoMnO_2$	$LiNiCoAlO_2$
Dimensions	18650	18650
SOC	50%	50%

IV.2. Manufacturer 1 cells packaging

The Manufacturer 1 cells were packed in cardboard boxes of 100 cells each. In an arrangement of 10x10 (see Figure 12). In the picture some cells were missing because they were taken out for some voltage checks. Every cell is isolated The separators between the cells are made out of a thin cardboard paper. 2 of these boxes are stacked on top of each other in one outer box made of corrugated cardboard. This outer box contains the hazardous materials labeling. The two inner boxes didn't contain any label

96 Batteries in one sub-box

Carboard paper dividers between every cell

2 sub boxes stacked on top of each other in one outer cardboard box

Figure 12: Manufacturer 1 cells packaging (the missing cells were taken to do some voltage checks)

IV.3. Manufacturer 2 cells packaging

Manufacturer 2 cells were packed in cardboard boxes of 100 cells each (see Figure 13). The cell rows are separated in one direction by a thick corrugated cardboard and in the perpendicular direction the cells are separated two by two by a thinner cardboard.

2 of these boxes are stacked next to each other in one outer box made of corrugated cardboard. Only this outer box contains the hazardous materials labelling.

100 Batteries in one sub-box

Corrugated Carboard dividers between every second cell

2 sub boxes stacked side by side in one outer cardboard box

Figure 13: Manufacturer 2 cells packaging.

IV.4. Pallets and Fire Containment Covers

A standard PMC pallet (dimensions: 243.8cm – 125in/317.5cm) shall be used. The fire containment cover shall have a height of 162.56cm (64in). The fire containment cover (FCC) shall be fixed to the pallet during the test as shown in Figure 14.
Refer to [3] for a technical data sheet of the FCC.

Figure 14: FCC mounted on PMC pallet

V. Test Program, specific instrumentation and results

V.1. Test sequence

The Test sequence is depicted in Figure 15. It reflects in principle the test plan outlined in deliverable D4a but also deviations from the test plan that were deemed necessary by the Consortium after coordination with EASA.

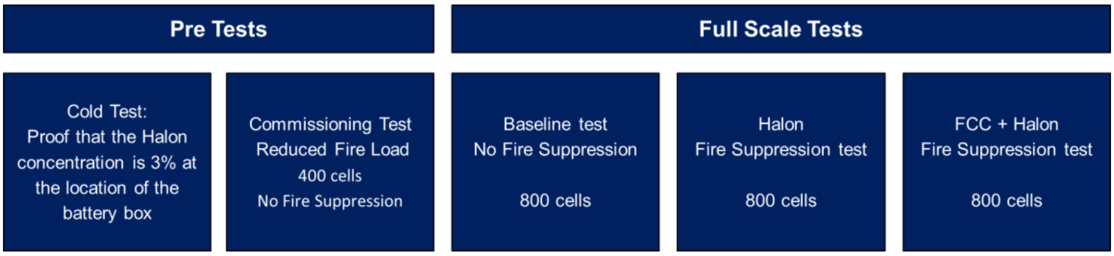


Figure 15: Test sequence for the Full scale test campaign.

Before starting the actual full scale test campaign, 2 pre-tests were performed. A **cold test** (without initiating fire) was performed to verify that the Halon concentration at every discharge point was higher than 3% which is the required concentration for Halon effectiveness in the aircraft.

The objective of the **commissioning test** which followed the cold test is to determine the minimum duration of the flame exposure to initiate some heat generation inside the box filled with cells. The commissioning test was performed with a reduced number of cardboard boxes and cells to identify the optimum test setup.

The objective of the **baseline test** is to assess the effectiveness of the Halon suppression system to suppress a battery cell fire initiated with an external flame. A further objective is to investigate the thermal behaviour of the cells after the fire suppression.

The objective of the final **full scale test** is to assess the effectiveness of both the Halon suppression system and the Fire Containment Cover. A further objective is to investigate the thermal behaviour of the cells inside the boxes.