SABATAIR

Deliverable 4b:

Lithium ion cell exposure to an on-board external fire: Test results

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

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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.

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)

Chapter I: Introduction

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 (ref. Deliverable 4a) 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.

I.1 Aircraft Fire Protection: Detection and Suppression

Fire detection systems are designed to alert the flight crew in the cockpit within 1 minute after the start of a fire. 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% in the compartment for a fire knock-down effect. Following this, a concentration of at least 3% must be maintained for the rest of flight. Maintaining the concentration of Halon is crucial to the effectiveness of the fire suppression system, and therefore it is essential that the cargo compartment is designed to be air-tight.

The phenomenon of thermal runaway of lithium batteries in an aircraft environment can be catastrophic [1]. In the case worst situation, thermal runaway in high density package of Lithium batteries can result - and has been implicated - in hull losses.

Tests conducted by the FAA Tech Center tests show that even a small number of cells involved in a thermal runaway event can emit gases that can cause explosions and fires that cannot be prevented or controlled by the aircraft fire suppression systems.

Chapter II: Test Chamber

II.1 Test Chamber Layout

All tests were carried out in a mock-up of an Airbus 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.

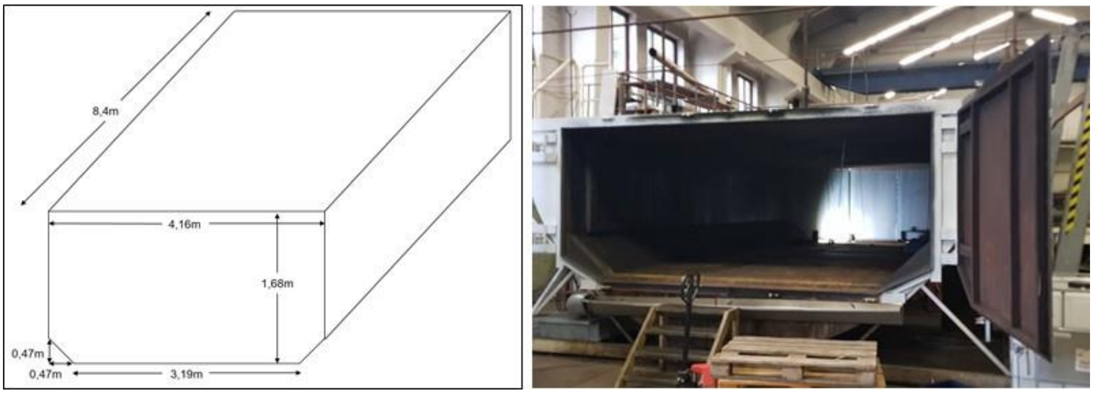


Figure 1: On the left a sketch of the fire test chamber and on the right a photograph of the fire test chamber

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.

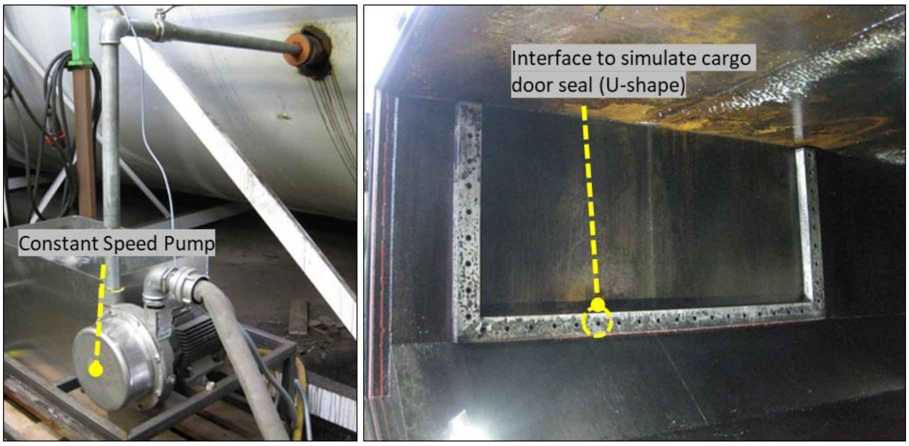
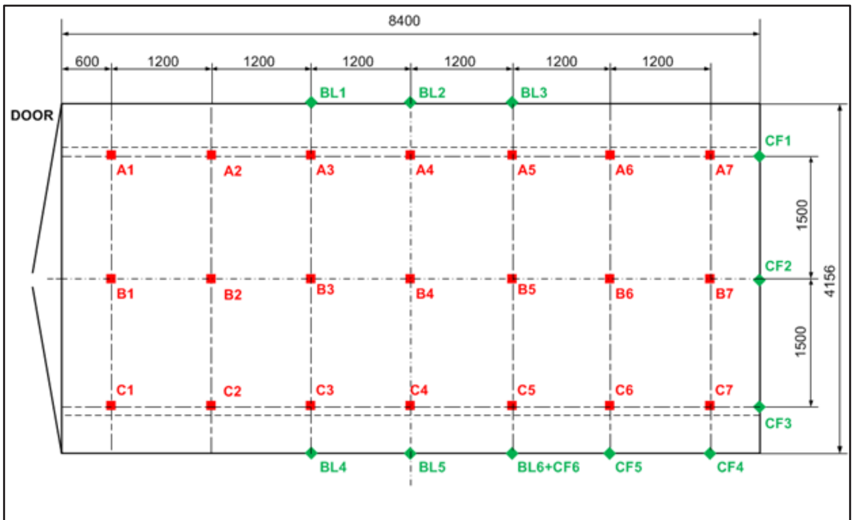


Figure 2. In-flight Leakage Simulation

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.



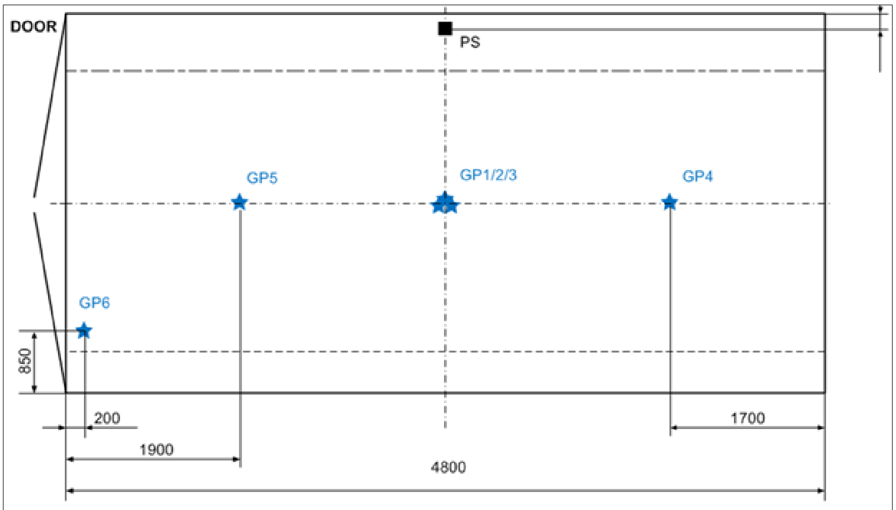
Thermocouple		Position and Configuration
■	A1 – A7 B1 – B7 C1 – C7	Ceiling thermocouples - 25mm below compartment ceiling
◆	BL1 – BL6	Sidewall thermocouples for Bulk-Load Fire Configuration; 305mm below ceiling – 25mm from sidewalls
◆	CF1 – CF6	Sidewall thermocouples for Containerized Fire Configuration;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

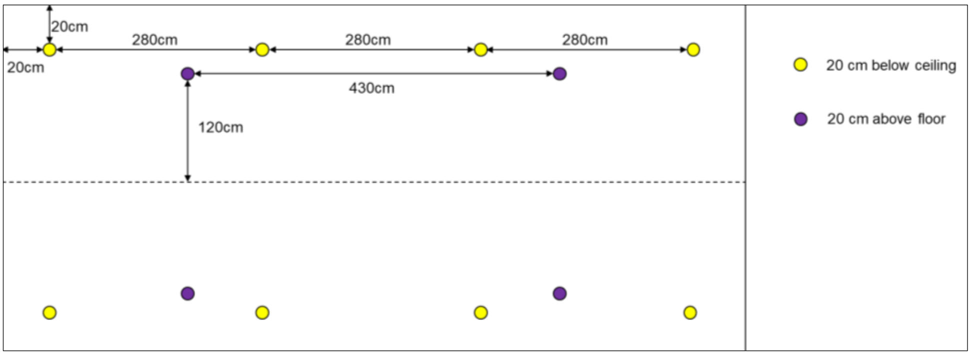


Figure 5: Halon Sensor location

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.

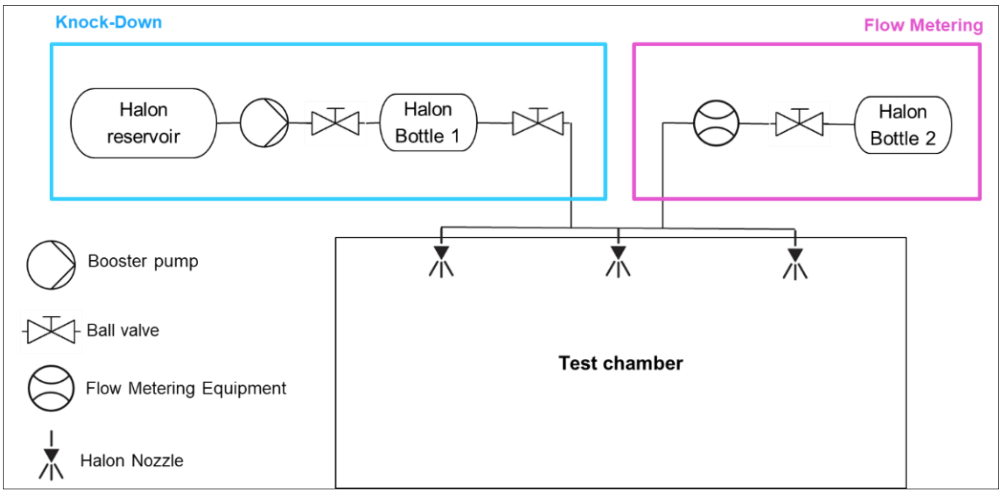


Figure 6: Schematic of the Halon Discharge system of the test chamber

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.

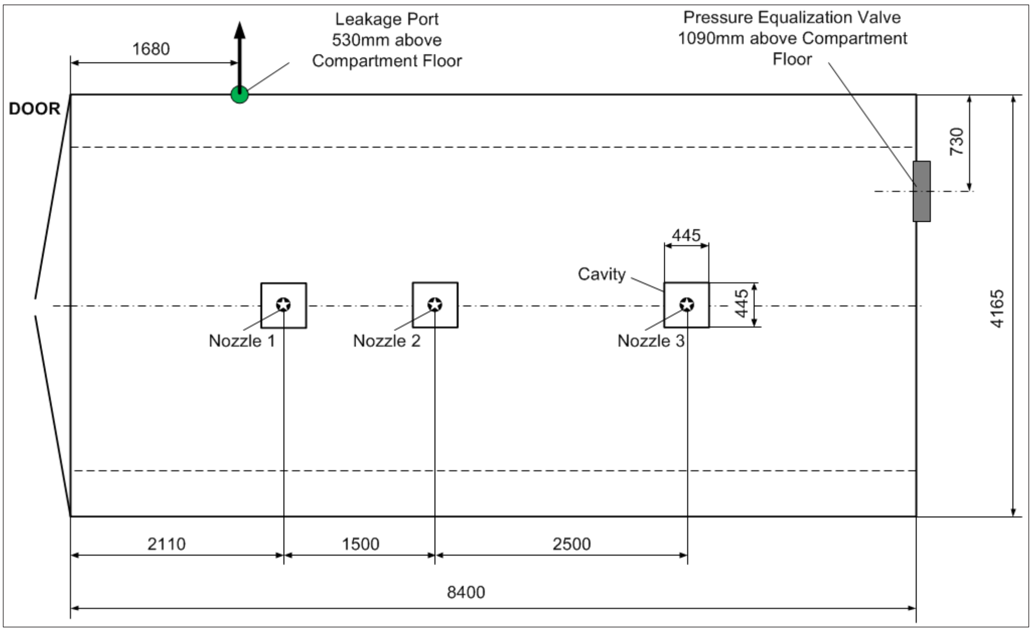


Figure 7: Position of Discharge Nozzles, Leakage Port, and Pressure Equalization Valve

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).

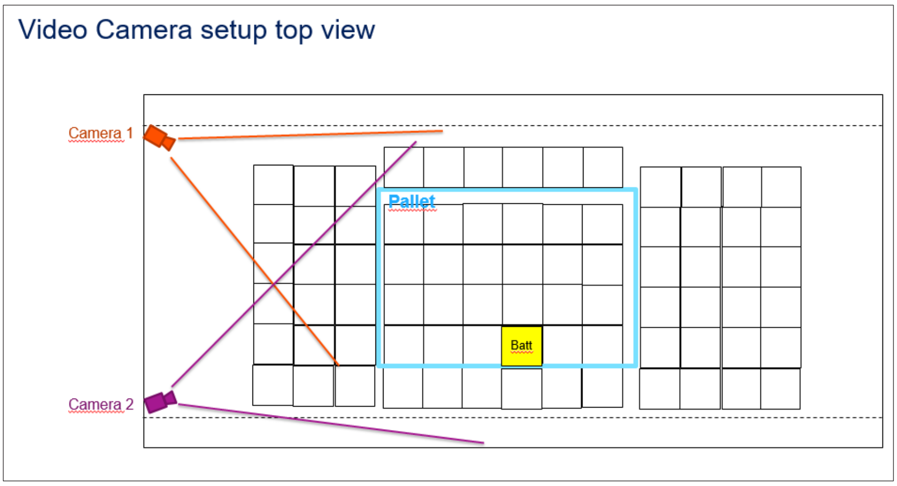


Figure 8: Video Camera instrumentation including field of view

Chapter 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].

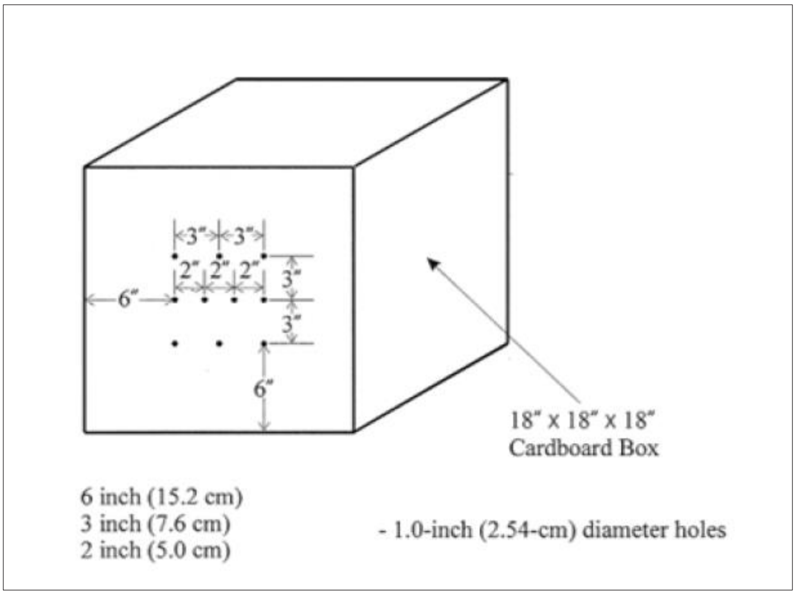


Figure 10: Ignition Box

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.

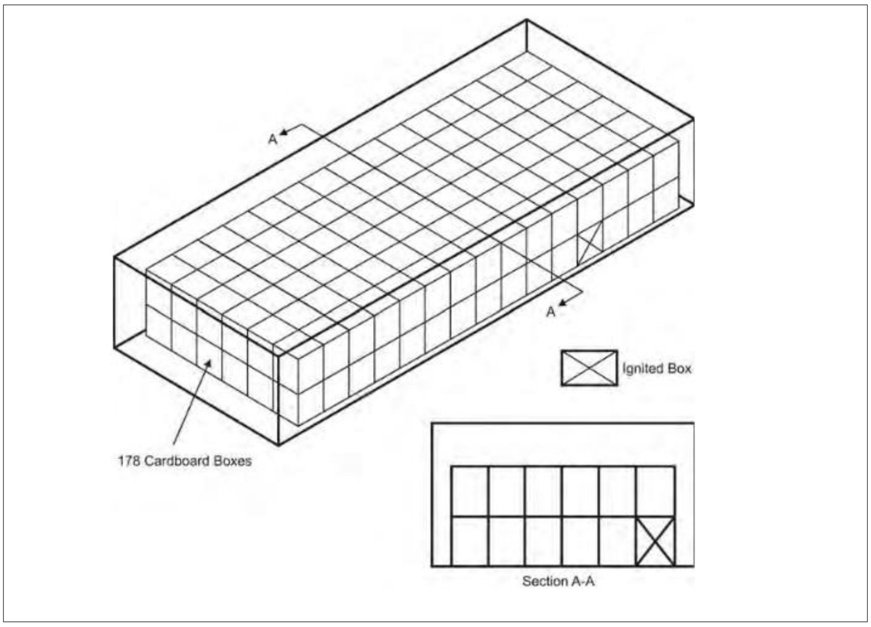


Figure 11: Arrangement of Cardboard Boxes as fire load for the Bulk load fire test of the Minimum Performance Standard for Aircraft Cargo Compartment Halon Replacement Fire Suppression Systems [2]

Chapter 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.1.1 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)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 labeling.

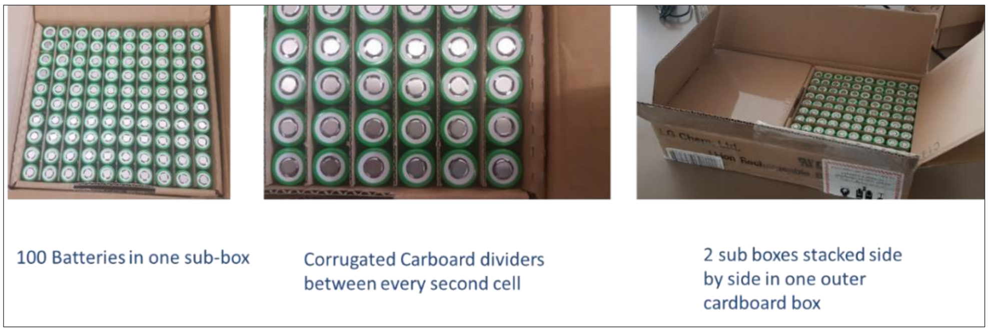


Figure 13: Manufacturer 2 cells packaging.

IV.2 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

Chapter 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.

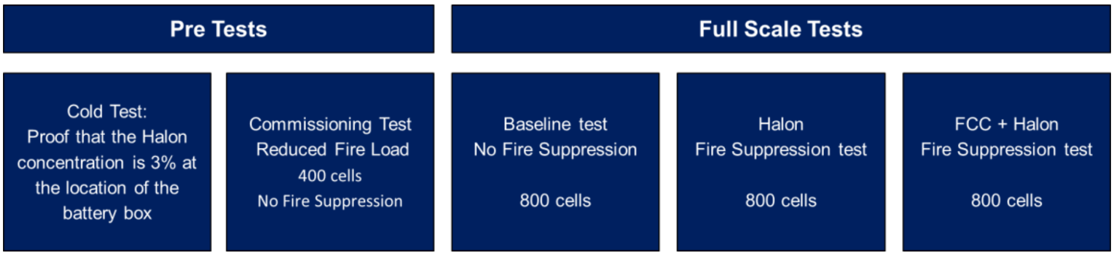


Figure 15: Test sequence for the Full-scale test campaign.

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.

V.2 Cold Test

The cold test in an empty test chamber without initiating fire was performed to verify that the Halon concentration at every installed measurement point is above 3% after 3 hours and the initial concentration is 5%. This is the requirement for ETOPS flights.

The reason for assessing the Halon concentration before the actual full-scale test is that it cannot be recorded real time during fire tests because the Halon sensors would be destroyed by fire byproducts.

V.2.1 COLD TEST PROGRAMME

The amount of Halon to be discharged from the high rated system part was 25kg. This corresponds to a representative system installed on commercial aircraft of comparable compartment size. The underlying formula is:

$M = \ln(1-c_a) \cdot (-V_c/V_a)$

where

M: required Mass of Halon

c_a: initial Halon concentration = 5%

V_c: Test Chamber volume = 56.6m^3

V_a: RT/p , R = 55.84, T = 291K, p=1023hPa

The Flow metering equipment with a pre-set flow rate shall be used to provide the flow-metered part.

V.2.2 COLD TEST PASS-FAIL CRITERION

The Halon concentration at every sampling point is equal or above 3% after 3 hours.

V.2.3 COLD TEST RESULTS

The cold test has been running for a total duration of almost 4 hours (3h55min) compared to the minimum requirement of 3 hours. The reason for extending the time duration was to evaluate margin.

It can be observed in Figure 16 that the Halon concentration curves show two clusters. One cluster of four plots shows a Halon concentration between 5.5% and slightly above 6%. This is the signal measured by the sensors close to the floor. The lower concentration which drops to almost 3% at the end of the test has been measured by the 8 sensors close to the ceiling. After approximately 4 hours, the Halon concentration in proximity to the ceiling is still above 3%. Figure 17 shows the values for the last 15 minutes of the test.

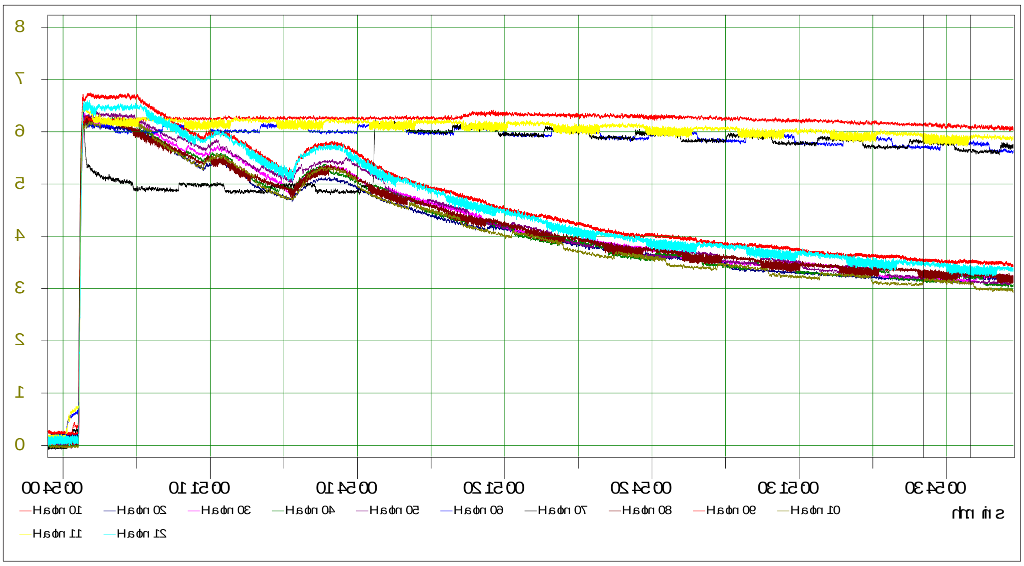


Figure 16: Measurement plot of the Halon concentration during the cold test

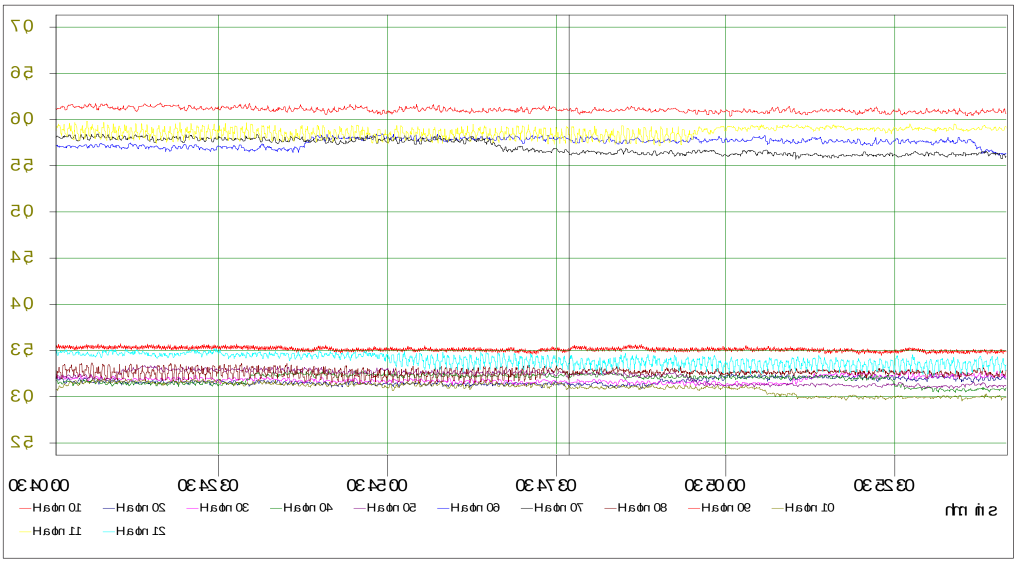


Figure 17: Halon concentration during the cold test (zoom on last 15 minutes)

V.2.4 COLD TEST CONCLUSION

The cold test is passed.

V.3 Commissioning Test

V.3.1 COMMISSIONING TEST - GENERAL

The objective of the test is to determine the minimum duration of the flame exposure to initiate some heat generation inside the box filled with cells and to find the optimum configuration of the ignition box relative to the cell boxes.

392 cells (200 Manufacturer 2 and 192 Manufacturer 1) shall be placed in proximity to the ignition box.

The fire suppression system is not activated during the commissioning tests.

V.3.2 COMMISSIONING TEST PASS-FAIL CRITERION

At least one temperature reading inside a battery box shall exceed 80°C.

V.3.3 COMMISSIONING TEST – BATTERY AND THERMOCOUPLE ARRANGEMENT

Figure 18 and Figure 19 show the thermocouple arrangement inside the boxes.

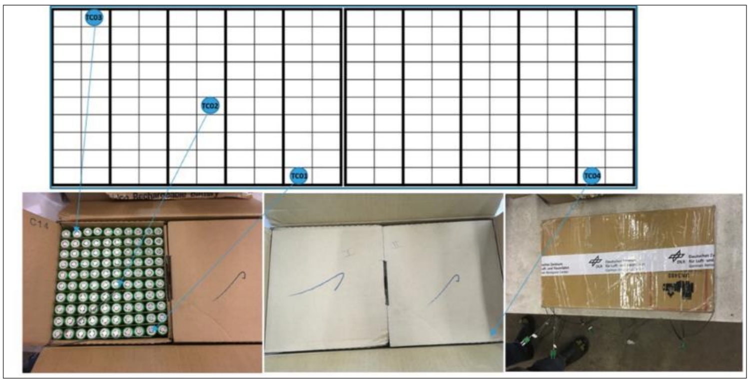


Figure 18: Thermocouple arrangement in the Manufacturer 2 box

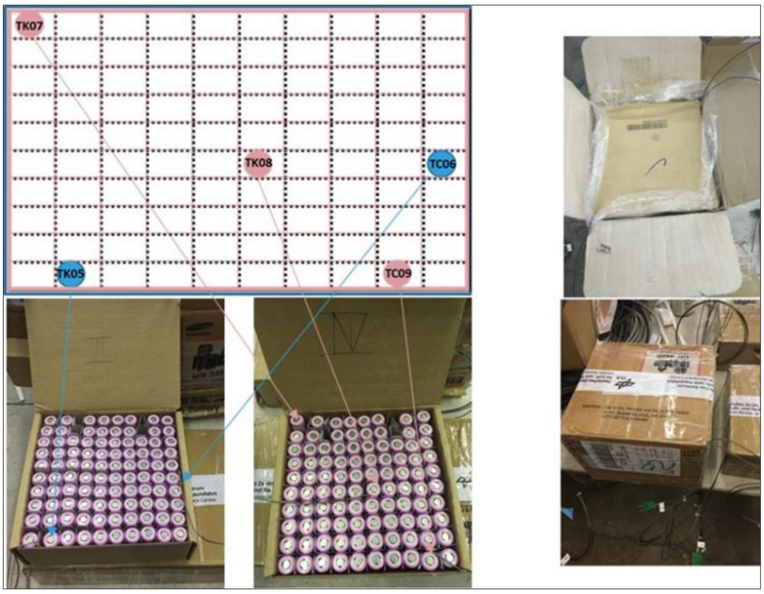


Figure 19: Thermocouple arrangement in the Manufacturer 1 box: Box III (on the bottom with blue lines) and box IV (on the top with bold pink lines) in their original shipping box

V.3.4 COMMISSIONING TEST #1

V.3.4.1 COMMISSIONING TEST #1 TEST SETUP

The cardboard boxes filled with shredded paper are arranged in a 5x4 matrix and in 2 layers (one on top of the other). One line of cardboard boxes is placed in between the ignition box and the battery box. The battery boxes (one Manufacturer 1 and one Manufacturer 2) are placed on top of a spacer.

The cardboard box arrangement during the commissioning test #1 is shown in Figure 20 to Figure 23.

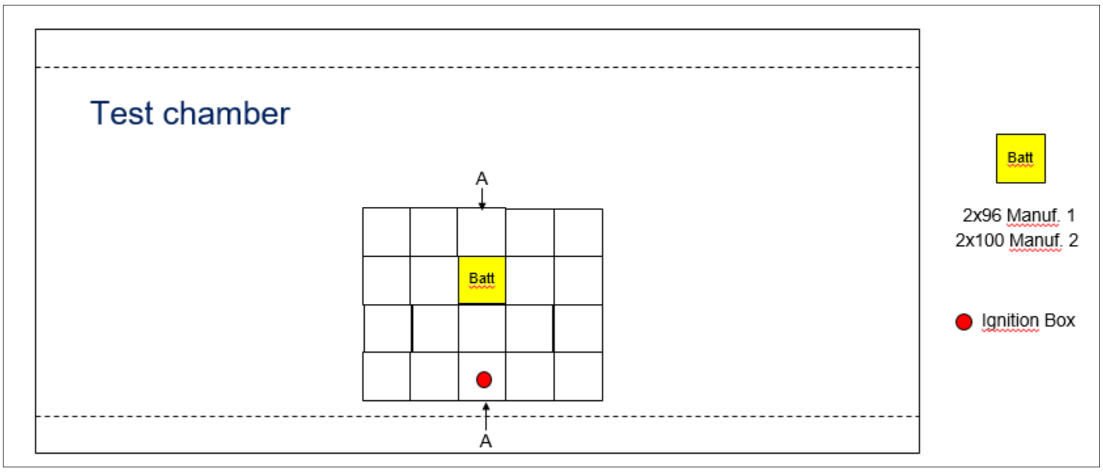


Figure 20: Commissioning test #1 setup top view

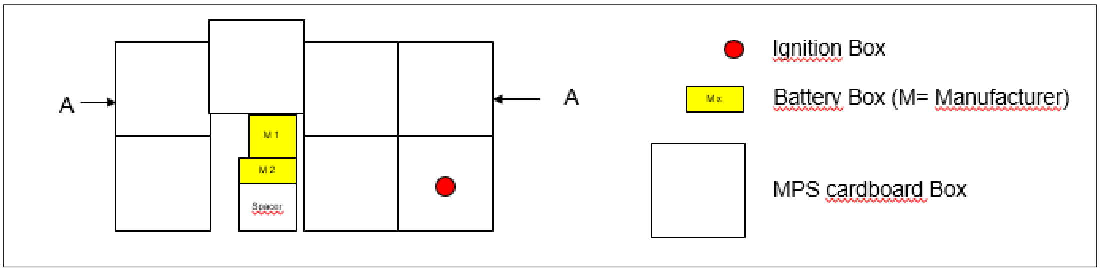


Figure 21: Commissioning Test #1 cardboard box setup cross-section A-A

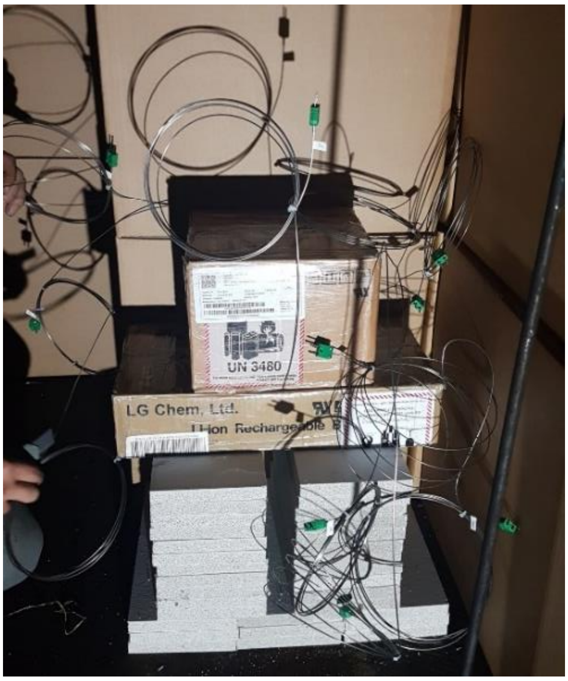


Figure 22: Boxes filled with cells on top of a spacer, test setup for commissioning test #1

Figure 23: Overall cardboard burn box arrangement for commissioning test #1

V.3.4.2 COMMISSIONING TEST #1 RESULTS

The pass-fail criteria for the commissioning test was not reached, the temperature measured inside the cell boxes stayed below 80 degrees. Due to the tightness of the compartment, the adjusted leakage rate was too low to allow for enough oxygen to support the burning process in a way to achieve a severe scenario in the chosen layout. After the test, the cell boxes were still intact, see Figure 24.

The commissioning test #1 was declared failed, so no measurement plots are presented here.

Figure 24: After commissioning test #1, the cell boxes were still unharmed by fire

V.3.5 COMMISSIONING TEST #2

V.3.5.1 COMMISSIONING TEST #2 TEST SETUP

For the commissioning test #2, the following modifications were made:

- The cell boxes inside the cardboard box were placed on a small spacer (see figure) and loose shredded paper was arranged around the spacer under the cell boxes
- The cardboard box containing the cell boxes was placed on top of a supportive structure, see Figure 28 to avoid that the cells falls on the ground in case the bottom box burns.
- The cell box was placed directly next to the ignition box

The cardboard box arrangement during the commissioning test #2 as shown in Figure 25 and Figure 26. Figure 27 and Figure 28 are pictures taken from the second commissioning test showing the cell boxes arrangement.

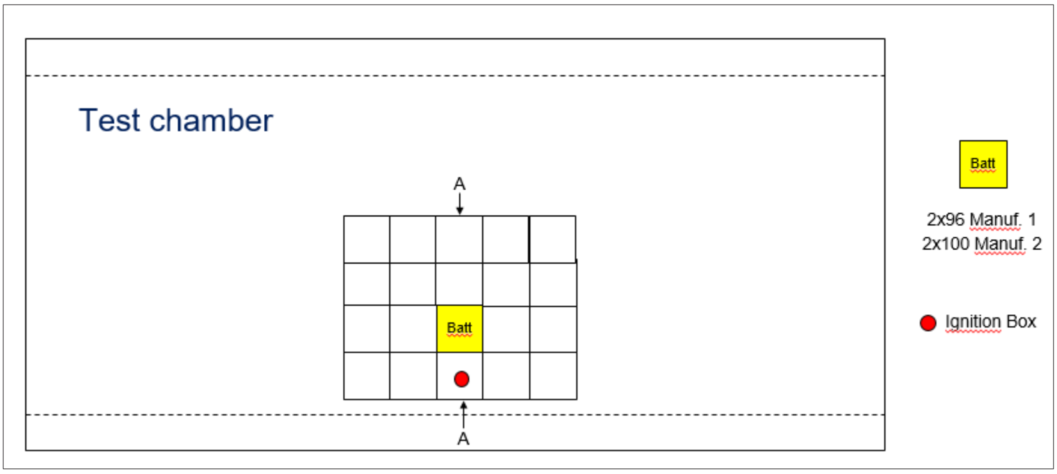


Figure 25: Commissioning Test #2 cardboard box setup top view

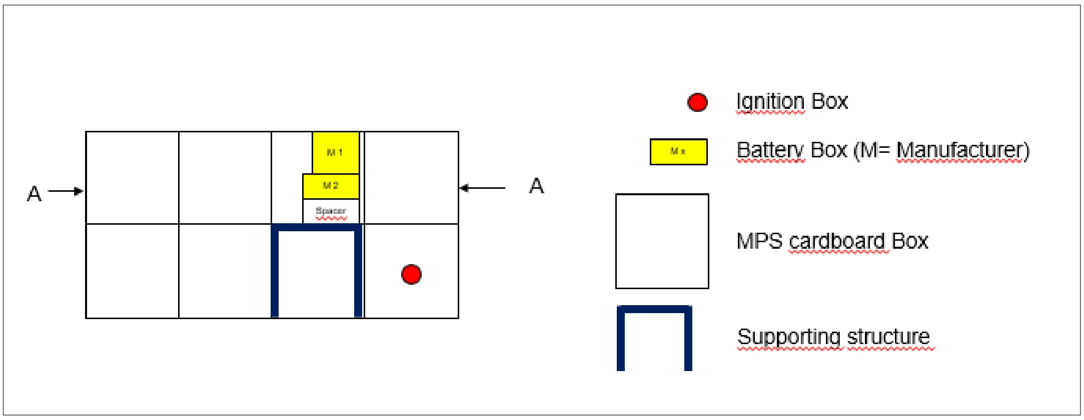


Figure 26: Commissioning Test #2 cardboard box setup cross-section A-A

Figure 27: Spacer and loosely packed shredded paper without (left) and with cell boxes (right)

Figure 28: Supporting structure for the cell box to allow for more oxygen ventilation

V.3.5.2 COMMISSIONING TEST #2 RESULTS

The pass-fail criteria for the commissioning test was not reached, the temperature of the temperature inside the cell boxes stayed below 80 degrees. Even with the modified test setup, the oxygen starvation was too high to allow for enough oxygen to support the burning process in a way to achieve a severe scenario in the chosen layout. After the test, the cell boxes were slightly more severely impacted than during commissioning test#1 but still no burn through from the outside to the inside of the cell boxes occurred, see Figure 29.

Figure 29: Cell boxes after commissioning test #2

The commissioning test #2 was declared failed, so no measurement plots are presented here.

V.3.6 COMMISSIONING TEST #3

V.3.6.1 COMMISSIONING TEST #3 TEST SETUP

The cardboard box arrangement for the commissioning test#3 was the same as for the commissioning test #2. The difference between commissioning test #2 and #3 was that additional oxygen has been injected into the test chamber to achieve a maximum burn rate. The chamber is able to be provided with 20l of forced oxygen flow. With this additional amount of oxygen, a worst case fire scenario was achieved.

V.3.6.2 COMMISSIONING TEST #3 TEST RESULTS

The test results protocol for commissioning test #3 is as follows (for the position of the thermocouples, refer to Figure 3, Figure 18 and Figure 19):

- TC T3 reached 80°C, 461,4 Seconds after Start of Ignition
- TC T1 reached 80°C, 317,64 °C Seconds after Start of Ignition
- TC C4 reached 93,3°C, 522,20 Seconds after Start of Ignition
- Ventilation Stopped 11 Minutes 55 Seconds after Start of Ignition
- Data acquisition Stopped 1 Hour 20 Minutes after Start of Ignition

The following figures (Figure 30 to Figure 33) illustrate the results of different parameters. The temperature values T10-T12 were recorded outside the cell boxes and do not contribute to the pass-fail criteria.

Similar to commissioning tests #1 and #2, it can be observed that there is oxygen starvation inside the chamber due to the fact that the burning process itself consumes oxygen which, at a certain point in time, is so low that the burning process of the fire load ceases. However, with the oxygen supply of 20l/sec during commissioning test#3, the fire load was sufficient to produce high enough temperatures at cell level. Some cells vented or went into thermal runaway. The pressure recordings show that the pressure rises when the fire is starting. When the fire slows down due to oxygen starvation, the pressure decreases and stabilizes afterwards.

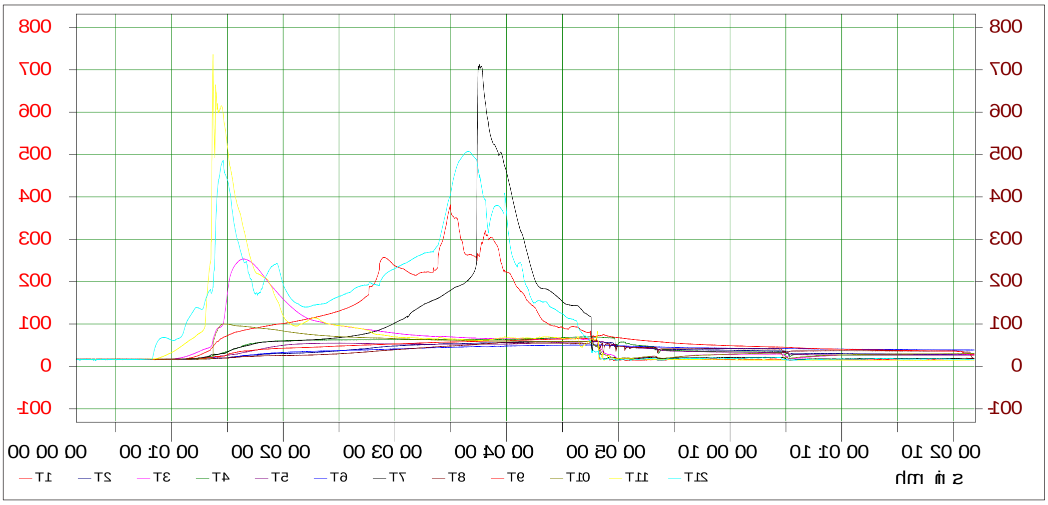


Figure 30: Cell temperatures for commissioning test #3

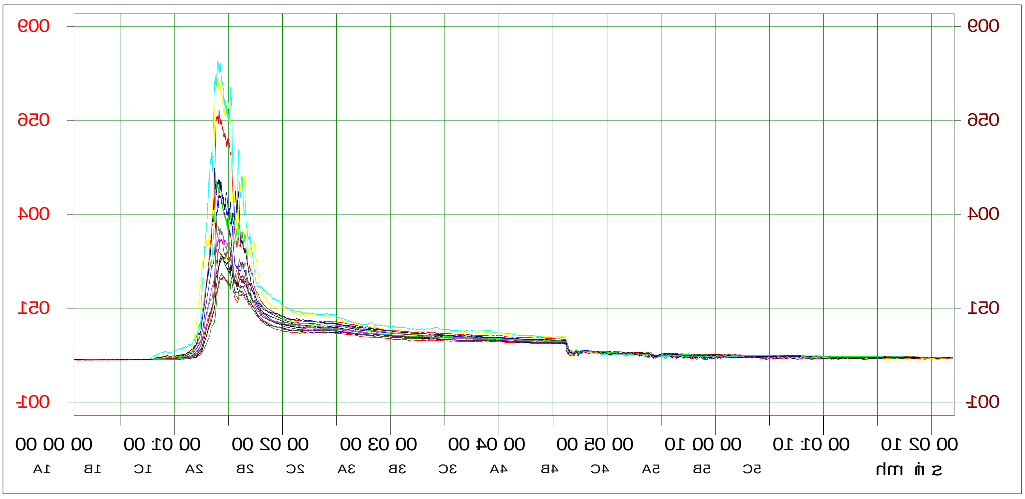


Figure 31: Chamber temperature measurements during commissioning test #3

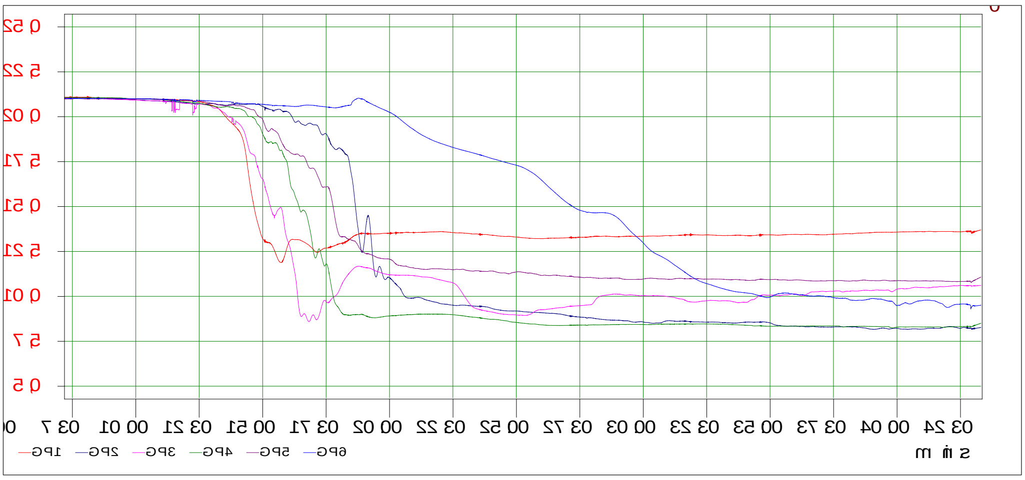


Figure 32: Chamber oxygen measurements during commissioning test #3

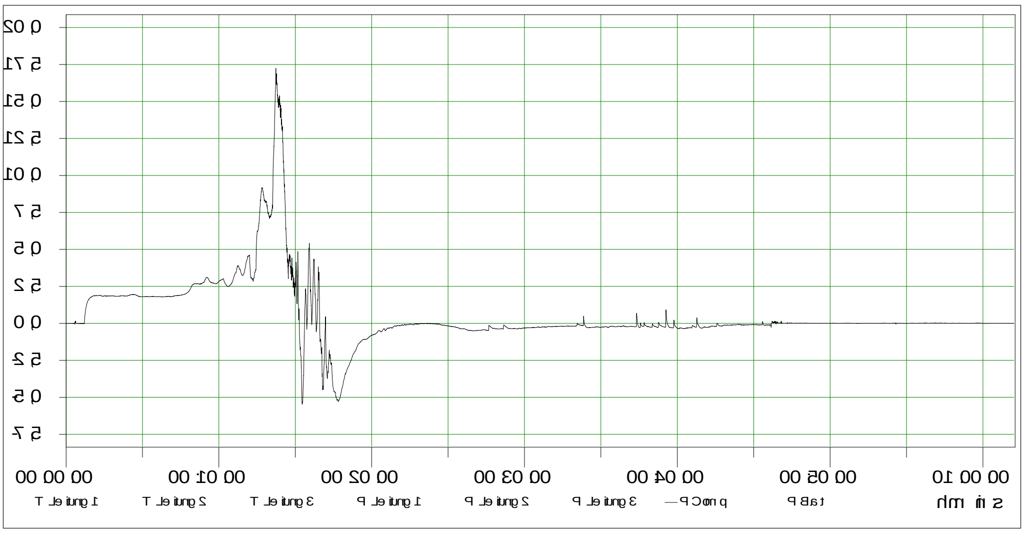


Figure 33: Chamber pressure measurement during commissioning test #3

On the photo documentation (Figure 34), it can be seen that a couple of cells vented or went into thermal runaway. The exact number of batteries involved was difficult to determine because during the test chamber fire extinguishing activity after the test, the cell boxes eventually did not stay in place. As approximation, around 3-4 cells went into thermal runaway and 10-15 cells vented.

Figure 34: Lithium cells after commissioning test #3

V.4 Full-scale External Fire Tests

V.4.1 TEST SETUP FOR ALL FULL-SCALE EXTERNAL FIRE TESTS

In total, 800 cells were involved per test. They were arranged in a way that they would receive as much energy from the ignition source as possible (see Figure 35). The cells were arranged in 2 layers, corresponding to the layers of cardboard boxes (see Figure 36 and Figure 37). The top layer of the cells was supported by the metal structure also used for the commissioning tests (see Figure 28) to prevent the cells from dropping when the cardboard boxes become unstable during the burning process.

For all full-scale external fire tests, the arrangement of the cardboard boxes was equal and similar to the requirements of the MPS test [2]. Deviating from the MPS arrangement, some cardboard boxes were placed on a pallet to allow installation of the Fire Containment Cover. Another deviation from the MPS arrangement was a third layer of boxes close to the ignition box. This third layer accounted for the properties of the fire containment cover. It allowed for an optimum coverage of the cardboard burn boxes with a minimum bending of the fabric (see Figure 37 and Figure 54).

Figure 35: Burning process inside the test chamber (Camera 2)

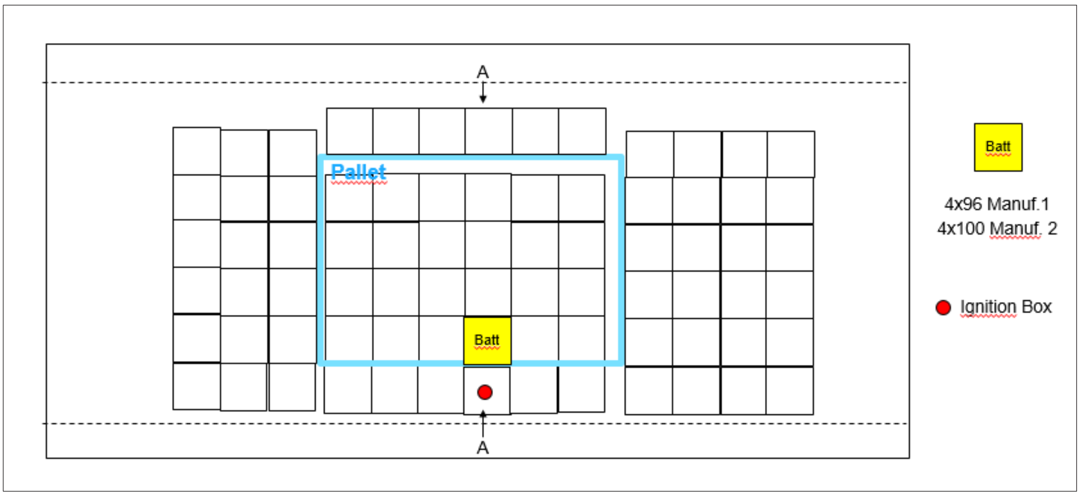


Figure 36: Arrangement of cardboard boxes for the full-scale fire test – top view

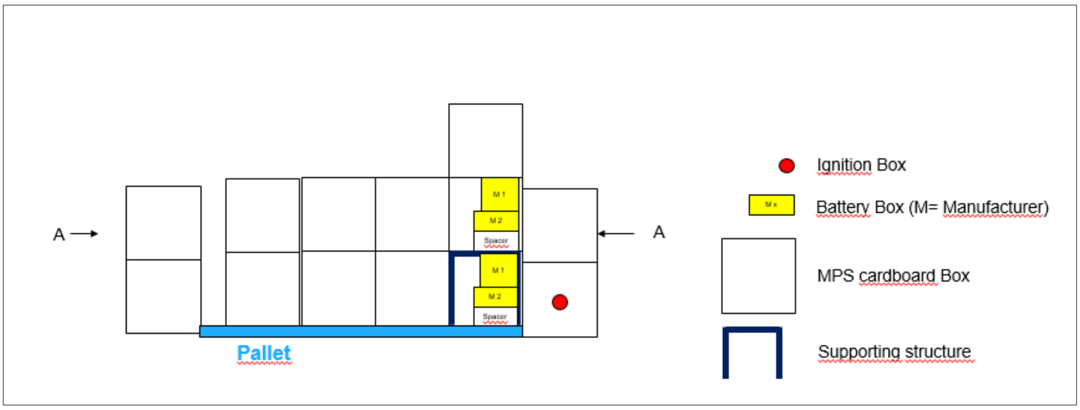


Figure 37: Arrangement of cardboard boxes for the full-scale fire test

The 12 available thermocouples for measuring the data of the battery boxes were arranged in an optimum way to retrieve temperatures and temperature gradients inside and outside of the battery boxes. The following figures illustrate the arrangement of the thermocouples inside and outside of the battery boxes.

In Figure 38 the blue positions indicate thermocouple location outside of the outer cardboard boxes. The pink/green positions indicate thermocouple locations directly on the respective cells (pink=Manufacturer 1, green=Manufacturer 2). The graphics also indicates the cells state of charge.

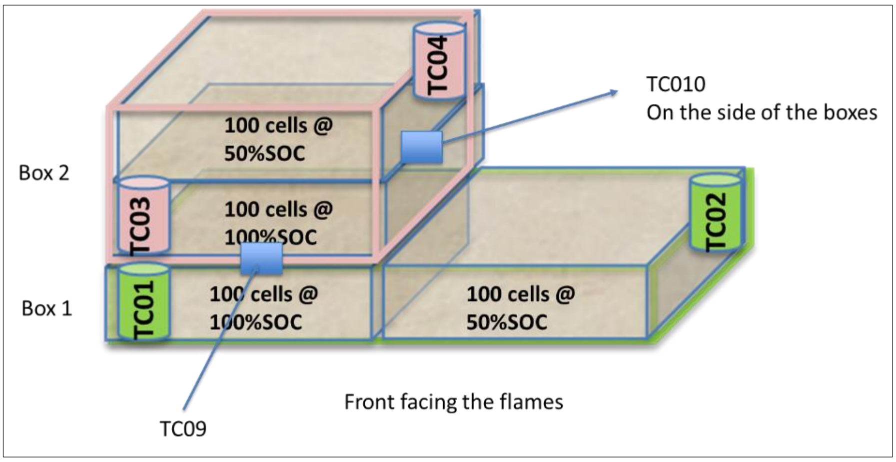


Figure 38: Position of the thermocouples of the cell boxes located directly on the pallet.

In Figure 39, the blue positions indicate thermocouple location outside of the outer cardboard boxes. The pink/green positions indicate thermocouple locations directly on the respective cells (pink=Manufacturer 1, green=Manufacturer 2) The graphics also indicates the cells state of charge. In a mixed configuration with 50 cells at 50% SoC and 50 cells with 100% SoC, the cells with 100% SoC were located at the outer rim as indicated in the upper left image.

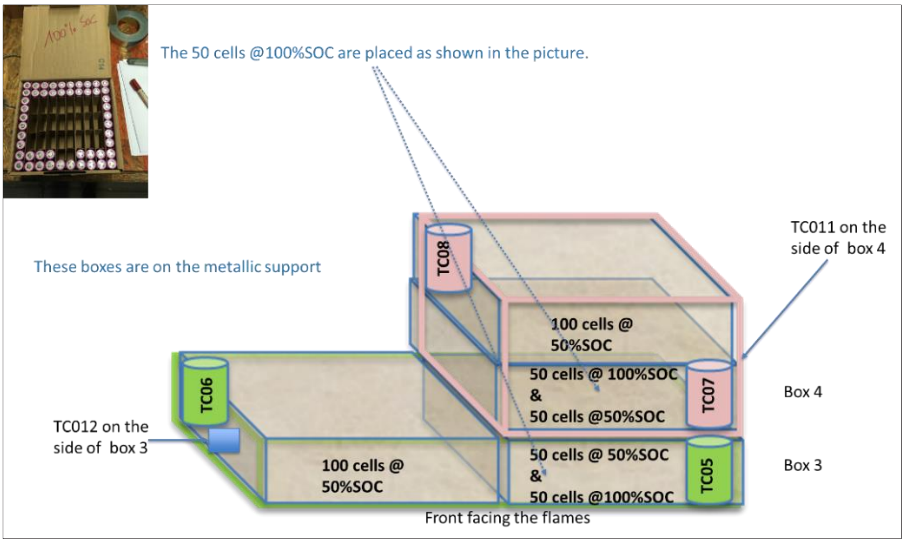


Figure 39: Position of the thermocouples of the cell boxes located on the metallic support.

V.4.2 BASELINE TEST RESULTS

Several temperature measurement points directly on the cells show readings in the order of magnitude of 700°C (see Figure 40). Although the exact amount of involved cells was not counted, it was estimated that around 100 cells went into thermal runaway. The cells located towards the ignition box were involved first (. As the test proceeded, thermocouples located in different boxes showed high temperature readings indicating thermal runaway of cells.

The test was stopped after approximately one hour. Cells were continuously involved during this time period. Thermal runaways obviously propagated throughout the packaging boxes without a tendency that this process would be interrupted.

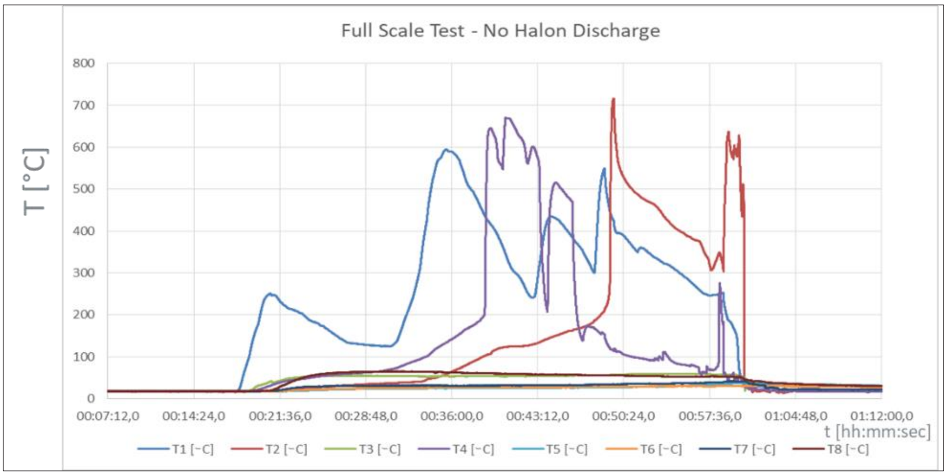


Figure 40: Temperatures at cell level during the baseline test

The temperature at the compartment ceiling showed values in the same range as in the cell boxes, see Figure 41. The temperature plot shows the typical profile. After a certain period of time, in this case approximately 5 minutes after the highest temperature elevation, the temperature decreases again. The cause for this effect is oxygen starvation. The oxygen needed for the burning process of the fire continuously decreases because of the tightness of the compartment, see Figure 42. The ventilation rate of 20l/sec is not sufficient to deliver enough oxygen to keep up the combustion process.

It must be noted that the ventilation is required to be shut off when a fire is detected in a Class C cargo compartment, therefore having a ventilation rate of 20l/s is creating more critical conditions than on a Class C cargo compartment of a large aeroplane, so the tested scenario can be regarded as a worst case.

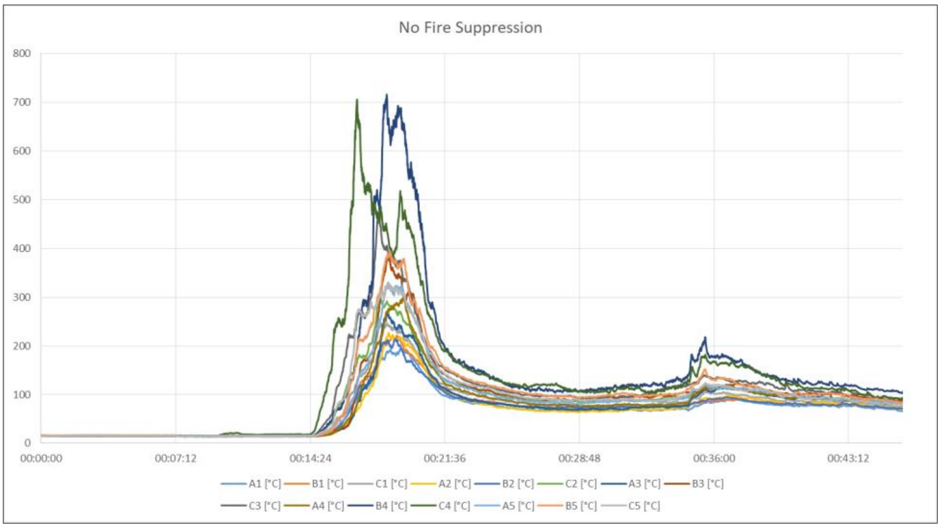


Figure 41: Compartment temperatures during the baseline test

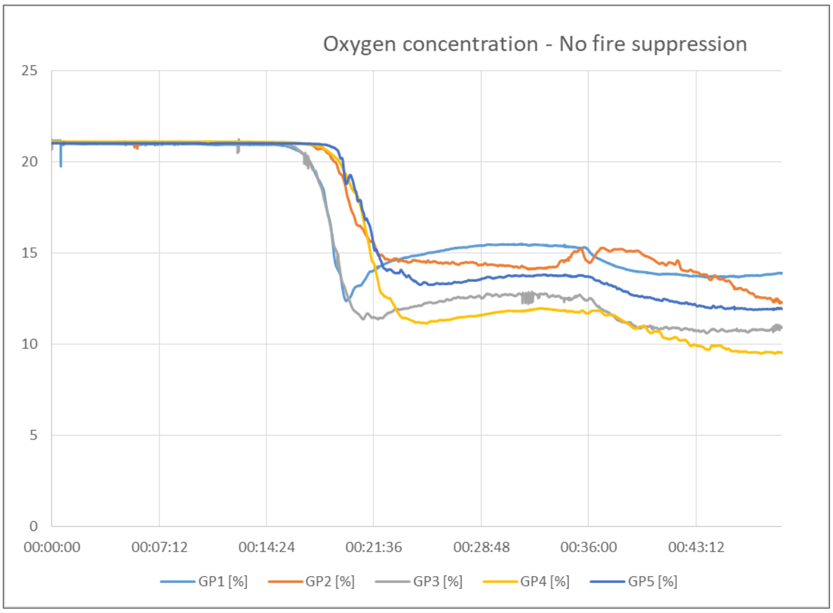


Figure 42: Oxygen concentration during the baseline test

The analysis of the cell boxes after the test showed significant damage, especially to the cells on the supporting structure (Figure 43 and Figure 44). The cells below the supporting structure were less involved (see Figure 45).

Figure 43: Overall impression of the cell boxes after the baseline test

Figure 44: Damage to cell boxes on supporting structure

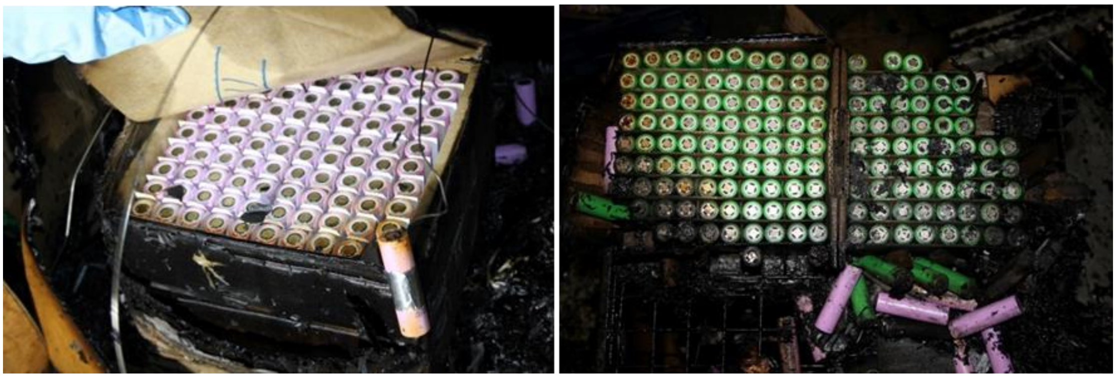


Figure 45: Damage to cell boxes below supporting structure

V.4.3 HALON FIRE SUPPRESSION TEST RESULTS

To achieve a worst case condition, the Halon fire suppression test was performed differently than defined in the MPS test [2]. Actually, the aircraft Halon fire suppression system was activated as soon as the temperature reading at the level of any of the cell thermocouples exceeded 145°C which was approximately 13 minutes after the actual Halon release criterium of the MPS test. This temperature was chosen because at this temperature, it can be assumed that a thermal runaway has already started. The thermal runaway was finally initiated and propagated between several cells.

This trigger criterion deviates from the trigger criterion in the MPS test [2]. The MPS requires the discharge of Halon one minute after a temperature of 93,3°C (200°F) at the ceiling level of the compartment has been reached. At the time this MPS criterion was reached, the temperature at any measurement point at cell level was far from being critical (30°C).

The Halon suppressed further propagation of thermal runaways. In the temperature profile recorded during the test, it can be observed that one reading reaches values that indicate thermal runaway. This reading is limited to a single high peak. As the test progressed, no further temperature rise was observed at any other measurement point. All thermal runaway processes occurred before the Halon discharge. The test was continued for 180 minutes after Halon discharge. This is the time over which the Halon system has to be shown to be effective.

Although the exact amount of involved cells was not counted, it was estimated that around 30 cells went into thermal runaway.

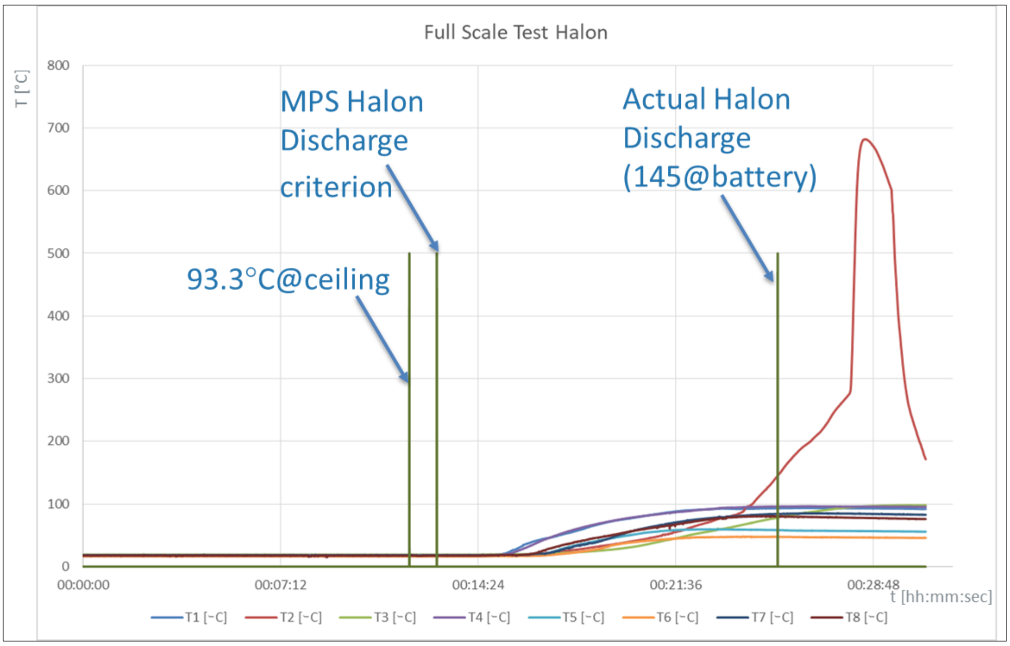


Figure 46: Temperature inside the cell boxes during fire suppression test (first 30 min)

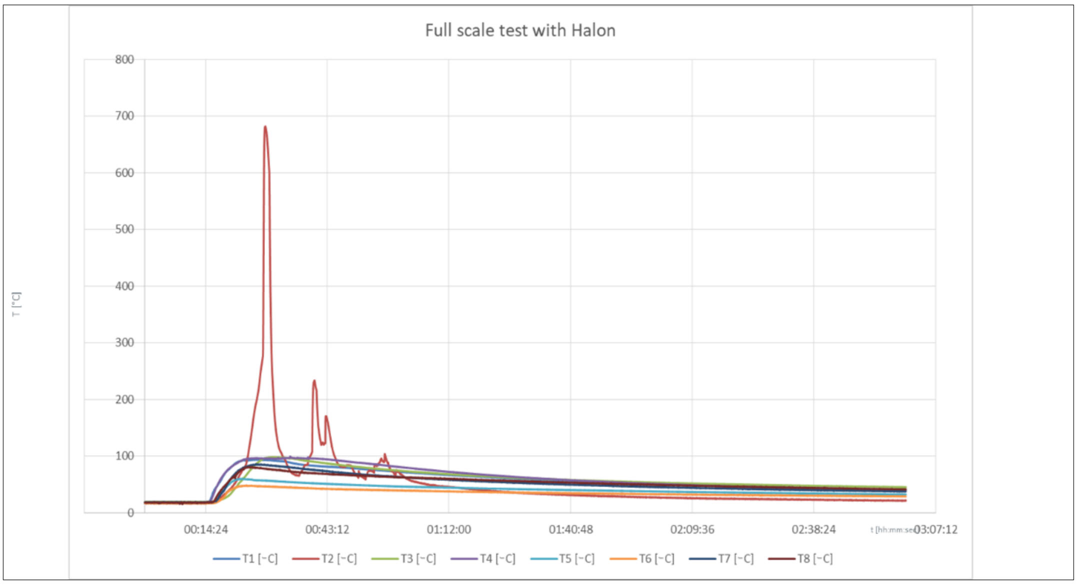


Figure 47: Temperature inside the cell boxes during fire suppression test – full duration

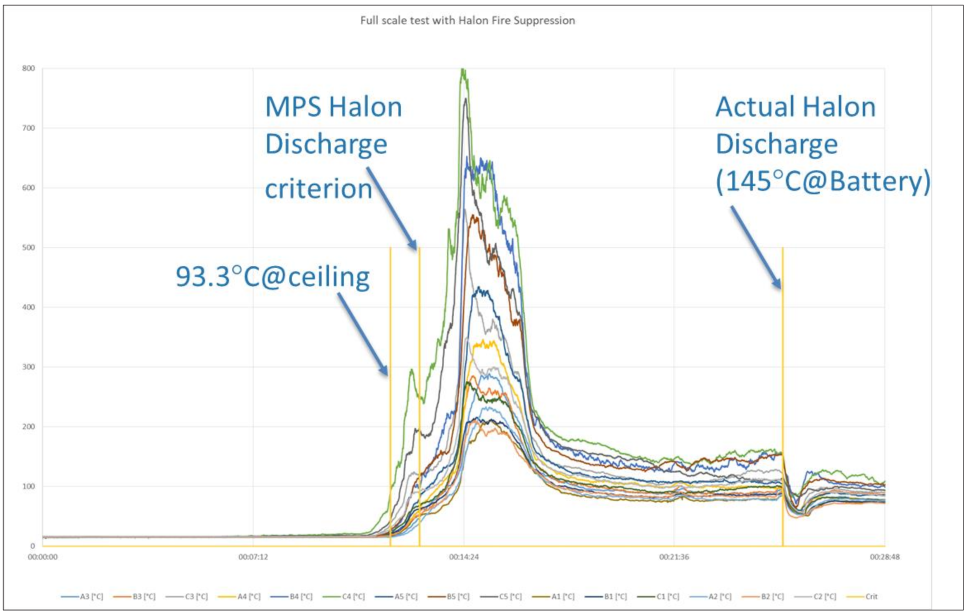


Figure 48: Temperature at ceiling level during fire suppression test (first 30 min)

Figure 48 shows the first 30 minutes of the temperature at ceiling level. The temperature does not increase anymore for the remaining test time even though Figure 47 shows 2 more temperature peaks after the first big peak.

93.3°C@ceiling

MPS Halon Discharge criterion

Actual Halon Discharge

Figure 49: Video still images of the Halon fire suppression test

Figure 49 shows a sequence of 3 still video images recorded inside the test chamber. At the time the ceiling temperature has reached 93.3°C, a very small flame is visible. At the time at which the Halon would have been triggered according to the MPS criterium, a bigger flame is visible. However, at this time, the temperature at cell level is still at approximately 30°C. At the time the temperature at cell level has reached 145°C (left image of Figure 49), no flame is visible. The fact that no flame is visible could either be caused by smoke which limits the visibility of the camera or an already reduced flaming caused by oxygen starvation.

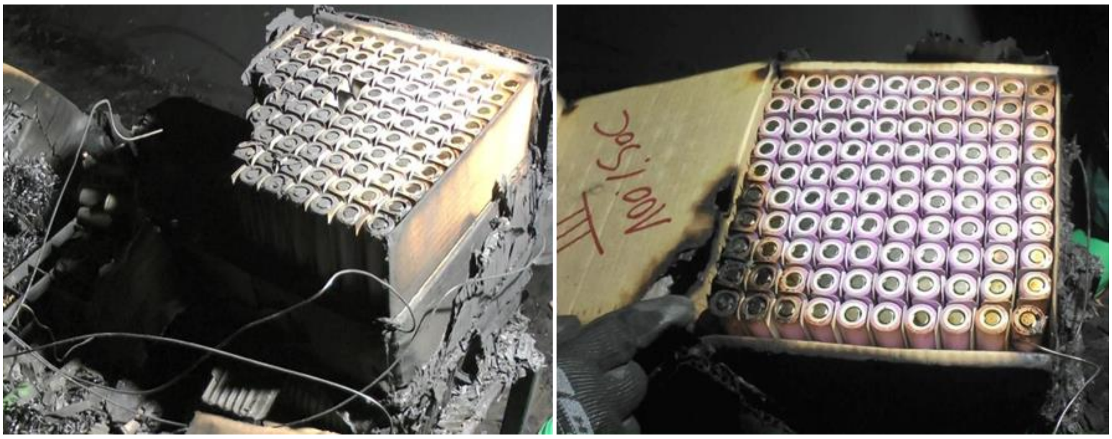


Figure 50: Top cell box and the box underneath after fire suppression test (Manufacturer 1)

Figure 51: The upper Manufacturer 2 cells after the fire suppression test

Figure 52: The Manufacturer 1 cell boxes under the supporting structure. The cells in the middle of the box are missing intentionally

Figure 53: The lower Manufacturer 2 Boxes

V.4.4 HALON FIRE SUPPRESSION AND FIRE CONTAINMENT COVER TEST RESULTS

Adding the fire containment cover to the test setup showed further improvement, resulting in the fact that the effects of the fire event on the boxes containing cells was reduced significantly.

The trigger criterion for the Halon discharge was taken from the previous test in terms of timing. The time from reaching a threshold temperature of 93.3°C for the Halon discharge was identical to the test without a fire containment cover in order to eliminate the influence of eventual thermal insulation caused by the cover itself.

The maximum temperature observed during this test was 145°C maximum in one location close to the ignition box. Analyzing the impacted cells after the test showed that only one corner of one battery box was affected and no thermal runaway had occurred.

Figure 54: Fire Containment Cover within cardboard boxes before the test

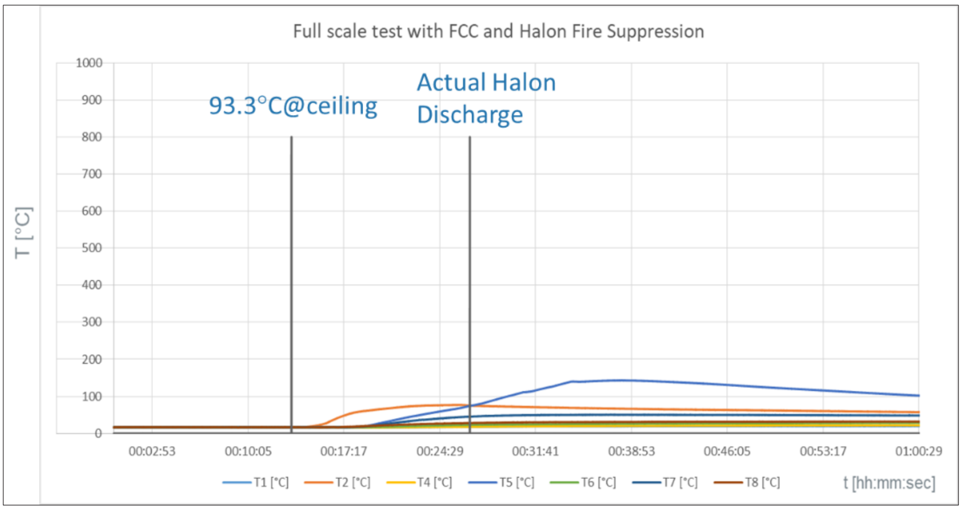


Figure 55: Temperature inside the cell boxes during fire suppression test (first hour)

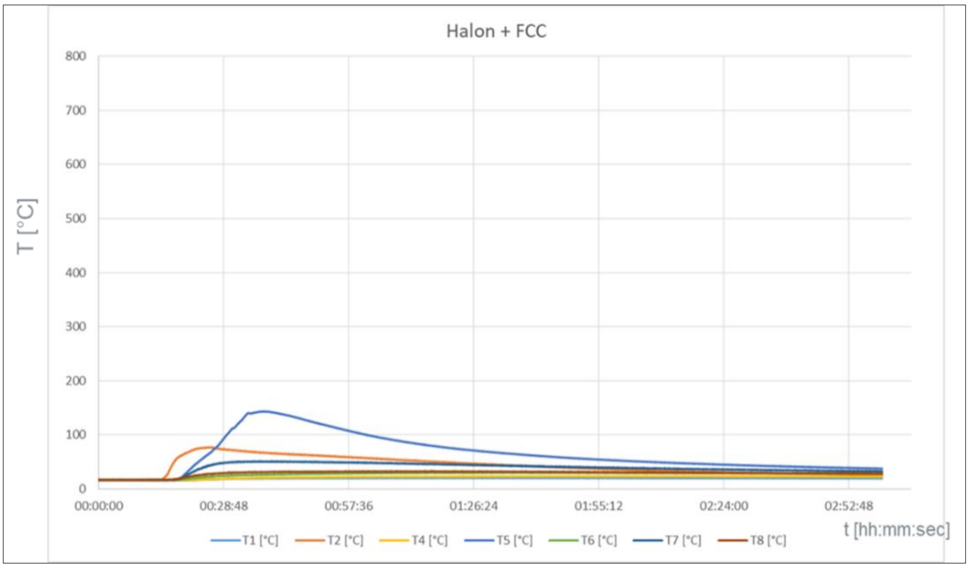


Figure 56: Temperature inside the cell boxes during fire suppression test (complete test duration)

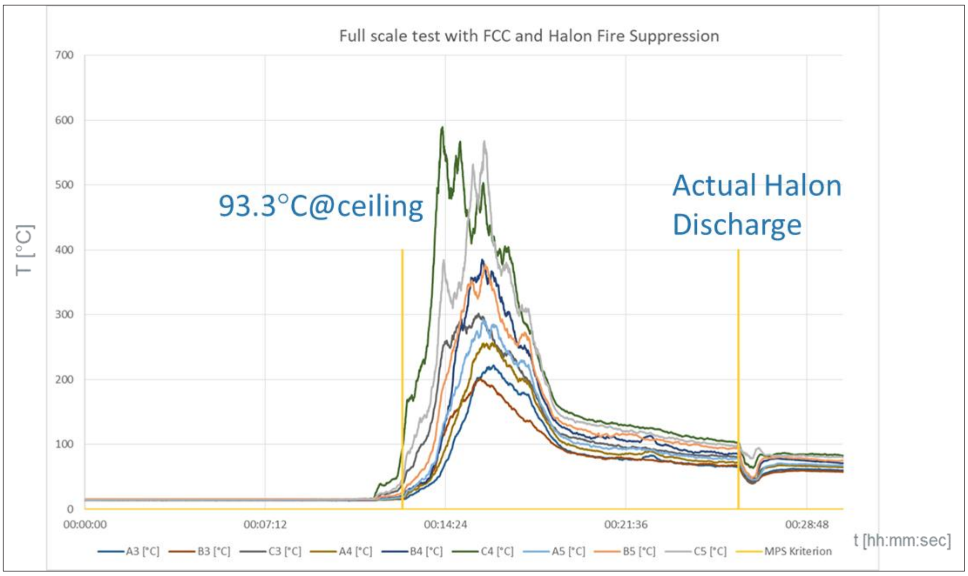


Figure 57: Temperature at ceiling level during fire suppression test (first 30 min)

The fire containment cover itself showed burn marks but was not burnt through. However, the temperature behind the cover was high enough to cause burn marks on cardboard boxes covered by the fabric of the cover.

Figure 58: Fire Containment Cover after the test

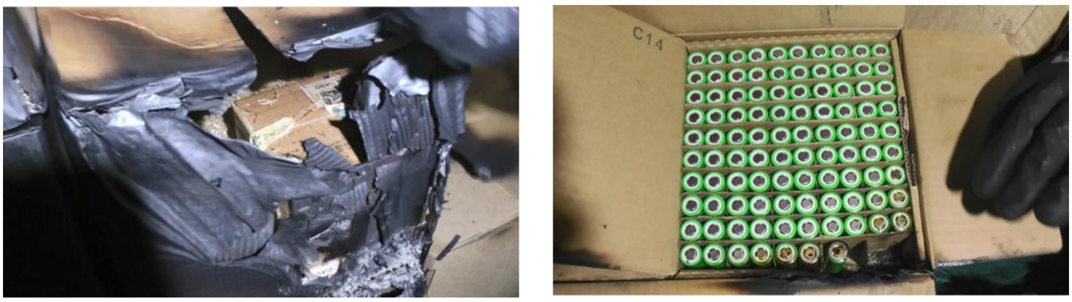


Figure 59: Impact on Cells after the Test with Fire Suppression and Fire Containment Cover

Conclusion:

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 significant appreciable protection against the threats of an external fire event.

Note on statistical relevance: each test was performed only once. The MPS test specification [2] requires every test to be conducted 5 times in order to gather statistical relevance. 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.

References

[1] SAFO - Safety Alert for Operators 10017, U.S. Federal Aviation Administration, Flight Standards Service Washington, DC, October 2010

[2] Minimum Performance Standard for Aircraft Cargo Compartment Halon Replacement Fire Suppression Systems (2012 Update), U.S. Federal Aviation Administration, DOT/FAA/TC-TN12/11, May 2012

[3] AmSafe Bridport FCC Data Sheet_AC80-0319111